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Developing RADARSAT's METOC Capabilities in Support of Project Polar Epsilon

B.G. Whitehouse, P.W. Vachon, A.C. Thomas
and R.J. Quinn

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Developing RADARSAT's METOC Capabilities in Support of Project Polar Epsilon

B.G. Whitehouse
OEA Technologies Incorporated

P.W. Vachon
Defence R&D Canada – Ottawa

A.C. Thomas
School of Marine Sciences, University of Maine

R.J. Quinn
National Defence Headquarters, D Space D

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Abstract

The Polar Epsilon project will use Canada's RADARSAT satellites to expand the Canadian Forces' space-based ship and oil spill detection capabilities in the Arctic, Atlantic and Pacific Oceans. RADARSAT's ability to detect ships and oil, however, is influenced by surface winds, waves and currents. As existing sources of meteorological and oceanographic data are too coarse in spatial resolution or too removed in time, this report investigates the feasibility of deriving such information from the RADARSAT imagery itself to conduct a rapid environmental assessment (REA) of (i) minimum detectable ship size and (ii) probability of oil spill false detection. The report also investigates methods to overcome limitations in Canadian Forces' deployed ocean observing infrastructure, which are required to develop and demonstrate space-based REA products, by using civilian ocean observing systems. In addition, as a means of decreasing limitations inherent in space-based synthetic aperture radar and ocean colour sensors used by Polar Epsilon (i.e. RADARSAT and MODIS), the report identifies and discusses meteorological and oceanographic features of military interest that may be detected by both types of sensors.

Résumé

Dans le cadre du Projet Polar Epsilon on utilisera les satellites RADARSAT du Canada pour étendre les capacités de détection depuis l'espace par les Forces canadiennes des navires et des déversements de pétrole dans les océans Arctique, Atlantique et Pacifique. L'aptitude du RADARSAT à détecter les navires et les déversements d'hydrocarbures dépend cependant des vents en surface, des vagues et des courants. Puisque la résolution spatiale des données météorologiques et océanographiques existantes est trop imparfaite et que l'obtention de ces données est trop différée, on étudie par la présente étude la faisabilité de dériver cette information de l'imagerie RADARSAT elle-même pour l'exécution d'évaluations rapides de l'environnement (REA) i) de la taille minimum détectable des navires et ii) de la probabilité de fausse détection de déversements de pétrole. Dans ce rapport on examine en outre les moyens de dépassement des limites de l'infrastructure d'observation des océans déployée par les Forces canadiennes, dépassements qui sont nécessaires pour l'élaboration et la démonstration de produits de REA basés sur des données acquises depuis l'espace et que permettra l'utilisation de systèmes civils d'observation des océans. De plus, à titre de moyens d'abaisser les limites inhérentes des radar à synthèse d'ouverture et capteurs de couleur de l'océan satelliportés utilisés dans le cadre du Projet Polar Epsilon (c.-à-d. le RADARSAT et le MODIS), on identifie dans ce rapport des caractéristiques météorologiques et océanographiques d'intérêt militaire que permettraient de détecter ces deux types de capteurs.

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Executive summary

Introduction

NATO engages in rapid environmental assessment (REA) to improve the performance of sensors and weapons. The Polar Epsilon project will use sensors on Canada's RADARSAT satellites to detect ships and oil spills in littoral waters, but their performance is influenced by the state of the ocean. Limitations in existing sources of METOC (meteorology and oceanography) data raises the question of extracting required environmental information from the RADARSAT imagery itself. RADARSAT is also capable of detecting METOC features that are of military interest and observable with space-based ocean colour sensors, such as MODIS. Atmospheric effects impede the use of MODIS, while RADARSAT has limited temporal resolution. Development of a fused RADARSAT/MODIS REA product would decrease these inherent limitations. Whether they be for ship, oil or feature detection, however, development and demonstration of REA products from space-based sensors requires extensive ocean observing infrastructure, some of which the Canadian Forces does not possess but is available within the civilian ocean observing community. In recognition of these technical barriers and the opportunity Polar Epsilon provides to overcome them, DRDC Ottawa placed a research contract to obtain definition and R&D recommendations.

Results

Surface winds, waves and currents influence the performance of RADARSAT, but wind has the greatest effect. Wind is currently the only one of the three that can be consistently derived from RADARSAT imagery. It is recommended that DRDC Ottawa develop and demonstrate a wind from RADARSAT REA product, which would be used to develop (i) an operational minimum detectable ship size product and (ii) an oil slick false target product. This will require wind data from auxiliary sources to initiate wind direction. Research to date is insufficient to recommend proceeding with an operational fused RADARSAT/MODIS product, but is sufficient to warrant proceeding with further definition and research. To do so, DRDC Ottawa will benefit from partnering with a military R&D facility that specializes in ocean colour. Canadian waters close to the USA have the greatest concentration of required operational civilian ocean observing infrastructure as in these waters data produced by American systems overlap into Canadian waters. The Gulf of Maine Ocean Observing System (GOMOOS), which includes waters of the Bay of Fundy and Southwest Nova Scotia, ranks foremost among these systems.

Significance

When applied successfully to Polar Epsilon, these findings will increase the Canadian Forces' operational surveillance capabilities and the user's confidence in space-based ship, oil and feature detection sensors used for purposes of security, defence and enforcement.

Future Plans

This Technical Memorandum is the responsibility of its authors and will be considered by DRDC Ottawa. It has the potential of leading toward a Technical Demonstrator Project.

Whitehouse, B.G., Vachon, P.W., Thomas, A.C., and Quinn, R.J. 2005. Developing RADARSAT's METOC Capabilities in Support of Project Polar Epsilon. DRDC Ottawa TM 2005-119. Defence R&D Canada – Ottawa.

Sommaire

Introduction

L'OTAN s'engage dans les évaluations rapides de l'environnement (REA) à des fins d'amélioration du rendement des capteurs et des armes. Dans le cadre du Projet Polar Epsilon on utilisera les capteurs à bord des satellites RADARSAT du Canada pour la détection de navires et de déversements de pétrole dans les eaux littorales, mais le rendement de ces capteurs est influencé par l'état de la mer. Les limites des sources existantes de données (météorologiques et océanographiques) du METOC soulèvent la question de l'extraction de l'information environnementale nécessaire de l'imagerie RADARSAT elle-même. Le RADARSAT permet en outre la détection de caractéristiques utiles pour le METOC qui sont d'intérêt militaire et observables au moyen de capteurs satelliportés de la couleur de l'océan comme le MODIS. Des phénomènes atmosphériques nuisent à l'exploitation du MODIS et le RADARSAT n'offre qu'une résolution temporelle restreinte. L'élaboration d'un produit de REA fusionnant des données RADARSAT et MODIS permettrait de repousser ces limites. Cependant, que ce soit pour la détection de navires, de nappes de pétrole ou d'autres caractéristiques, l'élaboration et la démonstration de produits de REA d'après des données de capteurs satelliportés exige une infrastructure évoluée d'observation des océans que les Forces canadiennes ne possèdent qu'en partie, mais qui est disponible dans la communauté civile d'observation des océans. Reconnaissant ces obstacles techniques et l'occasion offerte de les surmonter dans le cadre du Projet Polar Epsilon, RDDC Ottawa a accordé un contrat de recherche visant l'obtention de définitions et de recommandations de R et D.

Résultats

Les vents de surface, les vagues et les courants influencent le rendement du RADARSAT, mais c'est le vent qui a l'effet le plus important et il est le seul des trois facteurs qui puisse être pour le moment dérivé de l'imagerie RADARSAT avec les résultats souhaités. Il est recommandé que RDDC Ottawa mette au point et fasse la démonstration d'un produit de REA sur le vent dérivé de l'imagerie RADARSAT qui servirait à l'élaboration i) d'un produit opérationnel de détection de navires d'une taille minimale et ii) d'un produit sur les fausses cibles de nappes d'hydrocarbures. Cela exigera des données de sources auxiliaires pour la détermination initiale de la direction du vent. À ce jour les recherches sont insuffisantes pour recommander d'aller de l'avant avec un produit fusionnant des données RADARSAT et MODIS, mais elles justifient cependant d'autres travaux de définition et de recherche. Pour ce faire, RDDC Ottawa tirera avantage d'un partenariat avec une installation militaire de R et D spécialisée dans le domaine de la couleur de l'océan. Les étendues marines bordant le Canada et les É.-U. offrent l'infrastructure civile opérationnelle d'observation des océans la mieux développée, ce qui est a) pertinent pour les eaux canadiennes et b) nécessaire pour l'élaboration des produits de REA identifiés puisque dans ces régions, les données produites par des systèmes américains chevauchent les eaux canadiennes. Le Gulf of Maine Ocean Observing System (GOMOOS), qui couvre les eaux de la baie de Fundy et du sud-ouest de la Nouvelle-Écosse se classe au premier rang parmi ces systèmes.

Importance

Appliqués avec succès au Projet Polar Epsilon, ces résultats permettront aux Forces canadiennes d'améliorer leurs capacités opérationnelles de surveillance et assureront à l'utilisateur une plus grande confiance à l'égard des capteurs utilisés pour la détection depuis l'espace de navires, de

nappes de pétrole et d'autres caractéristiques à des fins de sécurité, de défense et d'application de règlements.

Projets à venir

Ce document technique n'engage que ses auteurs et sera pris en considération par RDDC Ottawa. Il pourrait mener à un projet de démonstration technique.

Whitehouse, B.G., Vachon, P.W., Thomas, A.C., and Quinn, R.J. 2005. Developing RADARSAT's METOC Capabilities in Support of Project Polar Epsilon. DRDC Ottawa TM 2005-119. R & D pour la défense Canada – Ottawa.

Table of contents

Abstract / Résumé i

Executive summary iii

Sommaire iv

Table of contents vi

List of figures and tables viii

Acknowledgements ix

1 Introduction 1

2 Polar Epsilon 3

3 Ocean observing for civilian and military purposes 5
3.1 Requirements 5
3.2 Rapid environmental assessment 6
3.3 Spaceborne sensors 10
3.3.1 Earth-observation satellites 11
3.3.2 Practical applications to REA 13

4 Obtaining METOC information with RADARSAT 16
4.1 Winds, waves, currents and features 16
4.1.1 Winds 16
4.1.2 Waves 17
4.1.3 Currents 18
4.1.4 Features 19
4.2 Practical issues 21

5 Obtaining METOC information with MODIS 22
5.1 Turbidity, colour, temperature and features 24
5.1.1 Sea-surface temperature (SST) 25
5.2 Practical issues 28

6 Using civilian ocean observatories in Polar Epsilon 30
6.1 Southwest Nova Scotia - a METOC / REA demo site 31
6.1.1 RADARSAT satellite imagery 32
6.1.2 Ocean colour and SST satellite imagery 32
6.1.3 Ships of opportunity 34
6.1.4 Auxiliary METOC data 34

7 Discussion and recommendations for DRDC Ottawa 36
7.1 RADARSAT REA program for project Polar Epsilon 36
7.2 METOC features from fused RADARSAT/MODIS products 39
7.3 Using civilian ocean observing systems 40

8 Acronyms 42

9 References 43

List of figures

1. Canadian domestic maritime surveillance zones....4
2. The REA concept of operations....7
3. REA within the recognized environmental picture....8
4. Polar-orbiting satellite sensor revisit time in Gulf of Oman....11
5. RADARSAT image with corresponding Quickscat data....19
6. Wind vectors from RADARSAT using Figure 5 imagery....20
7. Examples of MODIS Aqua chlorophyll and SST products....26
8. Examples of MODIS Aqua 250 m true-colour products....27
9. AVHRR sea-surface temperature map for GOMOOS area....33
10. Seawifs seven-day composite ocean colour map for GOMOOS area....33
11. Surface current radials produced by the GOMOOS SeaSonde HF radar....35

List of tables

1. Coastal activities having socio-economic value & METOC requirements....6
2. Evolution of tactical military oceanography within NATO....9
3. Non-classified marine spaceborne Earth-observation sensors....12
4. Civilian METOC satellite capabilities applicable to NATO REA operations....14
5. Accepted and tested MODIS algorithms....23
6. Example research products produced by the MODIS science team....23

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1. Introduction

Meteorological and oceanographic conditions have influenced the performance of naval sensors, weapons and vessels for as long as war has been waged at sea. Our ability to account for these influences, however, is limited by the techniques available to measure them.

The Polar Epsilon project will use Canada's RADARSAT satellites to expand the Canadian Forces' space-based ship and oil spill detection capabilities in the Arctic, Atlantic and Pacific Oceans[1]. In addition to detecting ships and oil spills, RADARSAT may be able to monitor meteorological and oceanographic conditions that influence its ability to detect ships and oil spills. These conditions also influence the Canadian Forces ability to operate various acoustic sensors, and they are relevant to programs operated by Environment Canada and Fisheries and Oceans Canada. This environmental information pertains specifically to sea-surface winds, waves, currents and METOC (meteorology and oceanography) features.

Wind, wave and current data are already provided by METOC forecasting models and sensors mounted on *in situ* and shore-based platforms and other Earth-observation satellites. But not necessarily at the same time, location and spatial resolution that RADARSAT is operating at. There lies the problem.

Polar Epsilon will operate RADARSAT in remote or denied areas where *in situ* and shore-based sensors may not exist, or where only covert sensors can be used. It will also operate the satellite at spatial resolutions of a few metres to 100 metres. Operational forecasting models and other types of satellite sensors that provide wind, wave or current data usually operate at spatial scales of 10,000 – 25,000 metres (i.e. 10 – 25 km), which can result in them not observing finer scale METOC features that may influence sensor, weapon and vessel performance.

This problem is not confined to remote and denied areas. Operational *in situ* sensors are in fact sparse world wide, and forecasting models and other types of satellite sensors usually operate at the same spatial resolution off of Vancouver as they do off of Tuktoyuktuk.

Although RADARSAT's ship and oil spill detection capabilities are being used operationally, its METOC capabilities are largely at the R&D stage of the innovation cycle. In part, this is due to deficiencies in required operational infrastructure and the limited temporal resolution of a single polar-orbiting satellite. But there is another equally stifling barrier. To date, the perceived operational value of these METOC capabilities has been insufficient to justify the substantial cost of acquiring the thousands of RADARSAT scenes required to monitor METOC conditions annually on an operational basis.

In support of its ship and oil spill detection objectives, Polar Epsilon will create the required operational infrastructure and receive approximately 10,000 RADARSAT-2 scenes per year. This in turn provides the opportunity to operationalize the satellite's METOC capabilities at minimal incremental costs. There lies the opportunity.

In addition to RADARSAT data, Polar Epsilon will collect METOC data from the MODIS (Moderate Resolution Imaging Spectroradiometer) sensor flown on NASA's Terra and Aqua

[1] RADARSAT-1 was launched in November 1995 and is still operational; RADARSAT-2 is scheduled for launch in 2006.

satellites. MODIS provides environmental information pertaining to the colour, turbidity and temperature of surface waters. This sensor is capable of providing operational information required by Canadian Forces naval and maritime platforms, antisubmarine warfare and mine countermeasures programs, and NATO amphibious warfare operations. In the context of this report, however, the relevance of MODIS is limited to its 250-500 m true colour channels and to the possibility of generating fused RADARSAT/MODIS METOC products on an operational basis. This is desirable as ocean colour data is inhibited by the presence of clouds whereas RADARSAT is not.

MODIS is also relevant to programs operated by Fisheries and Oceans Canada, which in one manner or another pertain to water quality and Canada's recently legislated ecosystem approach to the management of coastal environments (i.e. the 1997 Oceans Act).

Although Polar Epsilon is an initiative of the Canadian Forces, it will utilize civilian satellites, will be of benefit to civilian departments and will benefit from access to data collected by civilian *in situ* and shore-based sensors and environmental forecasting models. This places the Polar Epsilon project at the right place at the right time, as world wide governments are merging their civilian and military ocean observing capabilities in recognition of resulting operational efficiencies. This opportunity, however, requires definition.

This DRDC Technical Memorandum defines civilian and military operational requirements for RADARSAT and fused RADARSAT/MODIS METOC products, identifies aspects of operational ocean observing that are common to the Canadian Forces, NATO and the civilian community, identifies and prioritizes new operational capabilities that could arise from a Polar Epsilon METOC program, and provides technology development and demonstration recommendations designed to realize identified opportunities.

2. Polar Epsilon

As noted in Canada's 1994 defence white paper, space is an increasingly important component of global security. Department of National Defence and Canadian Forces' goals in the exploitation of space-based resources include national security, sovereignty protection and the fulfillment of Canada's commitments to NATO and the United Nations.

Canada's defence space policy has led to capabilities involving both military and commercial satellite systems, many of which have the potential to support joint wide-area surveillance missions but have yet to adequately address Canadian needs.

Initiated in 2004, the Polar Epsilon project will address this deficiency by combining the capabilities of civilian satellites and Canadian Forces C4ISR in near-real time. This will provide the Canadian Forces and other government departments with advanced operational space-based wide-area surveillance capabilities. As shown in Figure 1, the primary geographic areas of interest include the Arctic, Pacific and Atlantic Oceans out to 1,000 nm from shore. In addition to these North American littoral areas, Polar Epsilon will fulfill operational surveillance needs of navy, army and air force commanders operating in foreign littoral areas.

Polar Epsilon focuses primarily on the application of Canada's RADARSAT-2 satellite, thus its implementation schedule reflects the expected 2006 launch date for this satellite. The Canadian Government has directly invested $445 million in the RADARSAT-2 program. This investment will be realized through the provision of imagery products to government users, and it is estimated that Polar Epsilon will acquire on the order of 10,000 RADARSAT images per year by such means.

To exploit this imagery, Polar Epsilon will deliver the necessary equipment, training and concepts of operation. Data will be collected by satellite reception stations located on the east and west coasts and subsequently processed and delivered in near-real time to their respective Marine Security Operations Centre. Once received and processed, these data will be fused with information from other sources.

The overarching Canadian Forces maritime surveillance requirement is to detect, classify, identify and track ships. For all three zones depicted in Figure 1 – inner, middle and outer – Polar Epsilon will target ships greater than 25 metres in length, in low to moderate wind conditions. A trade-off exists between minimum detectable ship size and area coverage rate, thus vessel detection depends on beam mode selection. This chosen 25 m vessel detection size does not limit the operator from selecting finer resolution beams that may detect vessels as small as 10 metres, depending upon oceanographic conditions such as surface winds, waves and currents. In addition, electro-optical satellites will be available to Polar Epsilon to classify or identify targets when environmental conditions permit.

Polar Epsilon's target data latency (i.e. time delay from target illumination to contact reporting) is less than or equal to 15 minutes for maritime surface surveillance. Note that airspace surveillance requirements are addressed through Norad, and Polar Epsilon's land surveillance components are outside the scope of this DRDC Technical Memorandum.

The Marine Security Operations Centres provide operational services to both the Canadian Forces and other government departments. Polar Epsilon is designed to support the mandates of these other departments with surveillance capabilities pertaining to illegal fishing, pollution, smuggling, search and rescue, potential threats from the sea and environmental information (i.e. ocean intelligence [1, 2]).

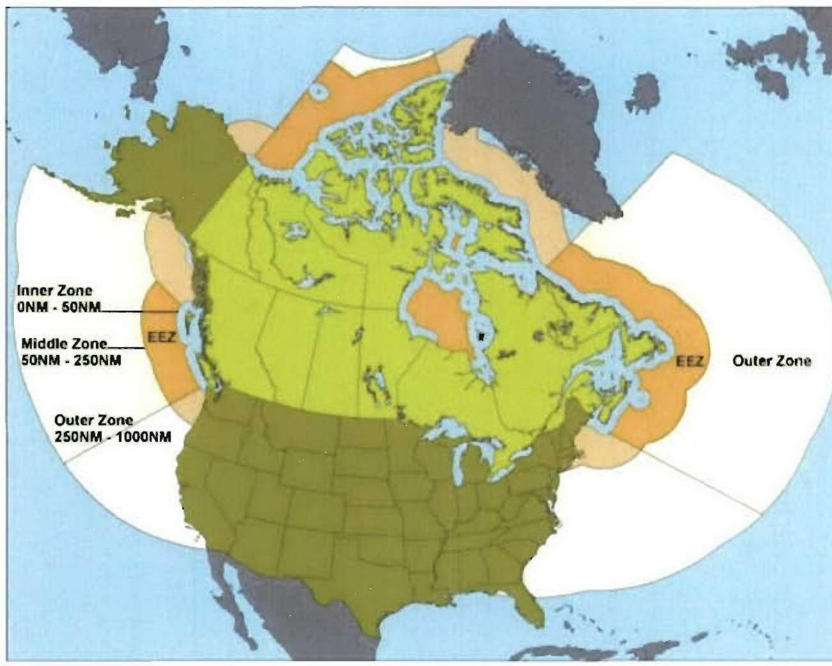


Figure 1. Canadian domestic maritime surveillance coverage zones. The figure is for illustration purposes only to define inner, middle and outer zones.

In addition to using the RADARSAT satellite for ship and oil spill detection, Polar Epsilon will exploit environmental sensing capabilities of the MODIS sensor mounted on NASA's civilian Terra and Aqua satellites. This aspect will focus on biological parameters, turbidity, sea-surface temperature and certain oceanographic features, such as fronts, eddies and internal waves.

In addition to the Marine Security Operations Centre on each coast, Polar Epsilon will have operational interfaces with Canadian Forces MetOc facilities (i.e. Halifax and Esquimalt) and the Joint Information and Intelligence Fusion Capability, the latter of which will produce a Common Operating Picture (COP) that incorporates information provided by Polar Epsilon.

3. Ocean observing for civilian and military purposes

The term *ocean observing* refers to systematic characterization of the marine water column and its boundaries – the atmosphere, shore and seafloor. In littoral waters, the open ocean is also a boundary. Collectively, this translates not only into detection of parameters and features in three dimensions of space, but also to observing their dynamics and forecasting their behaviour.

Ocean observing is a civilian term. NATO engages in ocean observing but addresses the subject in other terms, such as meteorology and oceanography. These terms address the same subject, but NATO requires environmental information for operational purposes – both strategic and tactical – and at times it operates environmental sensors in remote areas or covertly in denied areas. In addition, NATO has a global mandate whereas civilian ocean observing systems tend to be regional or national, although this situation is evolving, especially in oceanic environments.

3.1 Requirements

For both civilian and military purposes, marine environmental monitoring and surveillance sensors are required to observe environmental parameters, anthropogenic (i.e. human-induced) and natural features. Ships, oil spills and mines are but three examples of human-induced features. Table 1 identifies coastal activities that have (a) socio-economic value and (b) a critical or high requirement for ocean observing. Note that collectively these activities are both military and civilian in nature and that the two communities have common requirements. Among these activities, the *defence, security and enforcement* and the *education and research* sectors have the broadest METOC information requirements. As outlined in this report, the common METOC requirements of these two sectors provides the military with cost-effective development and demonstration capabilities through the use of civilian infrastructure and resources.

RADARSAT is capable of providing information pertaining to surface winds, waves, currents and METOC features. Table 1 indicates that surface winds are required for every coastal activity having socio-economic value, and that from a perspective of overall global demand, collectively surface winds, waves and currents represent three of the four top requirements.

MODIS is capable of providing information pertaining to water quality and surface temperature, two of the top six requirements in terms of overall demand. Water quality is a catch-all phrase that is ambiguous, but sufficient for the purposes of Table 1. From a military perspective its relevance pertains to the opacity of the water column and to the existence of bioluminescent organisms. Water opacity is relevant to anti-submarine warfare (ASW), submarine operations, amphibious operations and mine countermeasures (MCM). Bioluminescent organisms may influence detection of special forces and submarines.

Note that Table 1 lists METOC parameters but not METOC features, such as polar lows, oceanic fronts, eddies, turbidity plumes, etc. Instead, it references the key parameters that define or influence these features. Although there is strong commonality between the two, METOC features are addressed separately in this report because they differ in terms of their operational applications and detection techniques.

Table 1. Coastal activities having socio-economic value and their critical or high priority METOC requirements. Users are identified as two broad groups – publicly funded organizations ("public") and the private sector ("private"). Overall demand decreases with lighter shades of blue. We caution that *overall demand* is not the same as *priority within a specific sector*. See text for details.

COASTAL ACTIVITY	USERS	surface wind vectors	bathymetry	surface waves	surface currents	water quality	surface temperature	seafloor topography	sea ice	water turbidity	sub-surface currents	seafloor quality	surface salinity	sub-surface temperature	sub-surface salinity	internal waves
defence, security & enforcement	public	●	●	●	●	●	●	●	●	●	●	●	●	●	●	●
education & research	public	●	●	●	●	●	●	●	●	●	●	●	●	●	●	●
fisheries & aquaculture	public & private	●	●	●	●	●	●	●		●		●		●		
offshore oil, gas & minerals	public & private	●	●	●	●	●		●	●	●	●	●				●
climate change research	public	●	●		●	●	●		●		●		●	●	●	
coastal living, tourism & recreation	public & private	●	●	●	●	●	●			●		●				
waste & wastewater disposal	public & private	●	●		●	●		●		●	●		●			
oil spill response	public	●	●	●	●	●	●		●							
marine transportation	public & private	●	●	●	●				●							
marine-related utilities	public & private	●	●					●								
search and rescue	public	●		●	●		●									
storm surge / flooding	public	●	●	●												
mitigating accidents	public	●	●	●												

We caution that *overall demand*, as indicated in Table 1, is not the same as *priority within a specific sector*. The marine community's overall demand for water temperature, for example, is as shown, but this parameter is of highest priority within the anti-submarine warfare sector.

3.2 Rapid environmental assessment

In the mid 1980s, the U.S. Navy shifted its oceanographic focus from blue (i.e. oceanic) to littoral waters. This changed the focus of military meteorology and oceanography, initiated a renaissance in coastal monitoring and surveillance technologies, and gave rise to the subject of rapid environmental assessment (REA) [3].

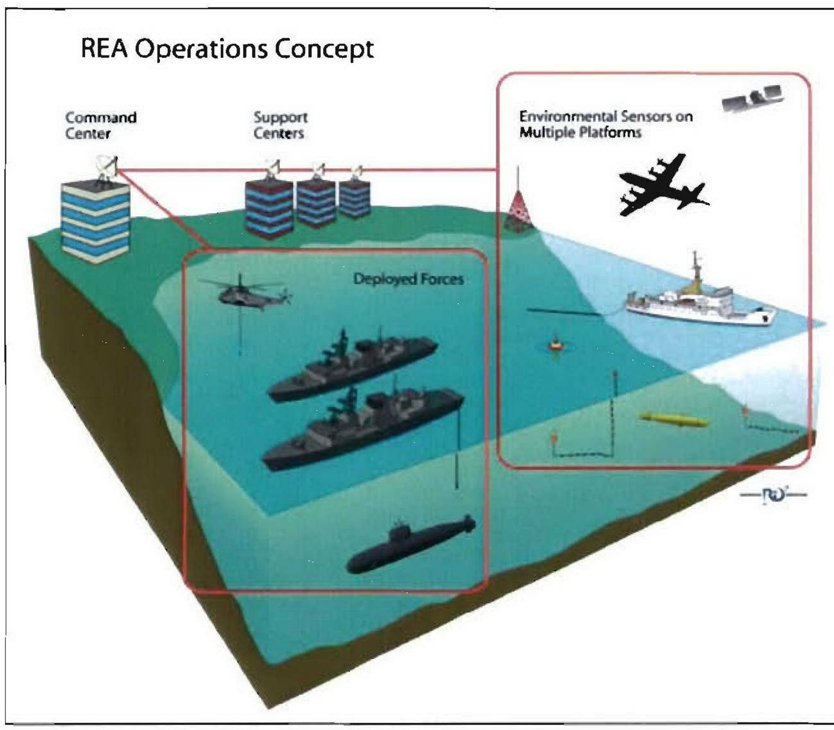
REA is a military-specific form of ocean observing and it is the present focus of NATO's METOC operations. By definition, it provides deployed forces with environmental information in littoral waters in tactical time frames. The U.S. literature uses the term warfighter instead of deployed forces, otherwise, the navies of NATO have developed a common view of REA. Critical to comprehension of the subject is understanding that the *rapid* in REA does not refer to the time scales of environmental variability or the duration of a military operation. It refers to the time available to respond to a request for environmental information.

From a NATO perspective, REA was born in 1995 when SACLANT (Supreme Allied Commander, Atlantic) identified it as a new requirement [4]. It emerged as a result of NATO's post cold-war shift in operations towards crisis response and littoral waters.

MARLANT MetOc has drafted a Canadian Forces REA policy paper which is undergoing formal review. To ensure interoperability, Canadian REA procedures closely mirror NATO procedures, with added emphasis being placed on the production of "quality-added" products or "impact products" vice the provision of data and information. Once reviewed and accepted, it is expected that REA will become Canadian naval doctrine. [personal communication, LCdr. Wayne Renaud, SSO, MARLANT MetOc]

NATO's REA concept of operations is depicted in Figure 2. The red lines represent NATO's spaceborne, ground-based and subsea data communications infrastructure.

Figure 2. The REA concept of operations based on NATO's EXTAC 777, but modified to recognize the role of the bottom boundary layer, underwater vehicles, shore-based and other platforms [5]. Graphics courtesy of DRDC Atlantic [3].



Replacing the military vessels and terminology used in Figure 2 with civilian vessels and terminology, and recognizing the red lines as civilian communications infrastructure, transforms this figure into a representation of civilian ocean observing systems. From a structural perspective, they are similar. Both are also very expensive to install and maintain. As a result of these and other factors, nations are moving away from duplicate ocean observing infrastructure to meet military and civilian requirements. The infrastructure that is emerging today includes both military and civilian resources, but has restricted access to certain components.

REA forms a large part of NATO infrastructure designed to provide allied command with the so-called Recognized Environmental Picture (REP). This concept is depicted in Figure 3. It shows that REA, which includes capabilities shown within the large oval, is a subset of the REP.

If NATO's relevant operational infrastructure is viewed at an even broader scale, it is seen that the REP is in turn a component of NATO's overall Recognized Maritime Picture (RMP). A commonality between the three – REA, REP and RMP – is that they all deliver geospatial data in littoral waters in tactical time frames.

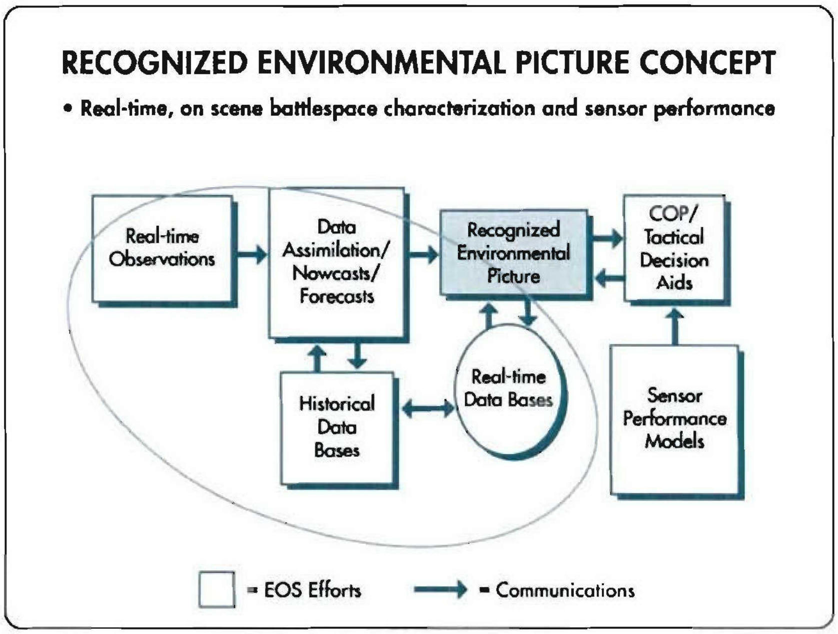


Figure 3. REA within the context of the Recognized Environmental Picture (REP). REA includes activities contained within the large oval. EOS = Expeditionary Operations Support. COP = Common Operating Picture. Based on graphics courtesy of Dr. Peter Ranelli, NATO NURC, Italy (NATO unclassified)

The broader the scale at which this military environmental infrastructure is considered, the more removed it becomes from the civilian ocean observing community. In other words, the greatest commonality between civilian and military ocean observing systems are the initial environmental data collection, processing, storage and distribution activities (i.e. within the REA component, as depicted in Figure 3). It follows then, that the greatest mutual benefit for the military and civilian communities arises when respective data collection, processing and distribution resources are interoperable. This has been recognized and is leading to open source operating capabilities and Web-based data and information products, both within the civilian and military communities.

From a Canadian federal perspective, the relevant departments within these two communities are the Department of National Defence, Environment Canada, Transport Canada and Fisheries and Oceans Canada, the latter of which includes the Canadian Coast Guard and the Canadian Hydrographic Service. Federally-mandated operations that may require such common infrastructure include participation in NATO and UN operations, search and rescue, weather forecasting, ocean forecasting, sovereignty promotion, fisheries enforcement, habitat monitoring, and responding to man-made and natural disasters, such as oil spills and coastal flooding.

NATO's inaugural REA product requirements addressed activities pertaining to anti-submarine warfare, mine warfare and amphibious warfare [5], however, this publication is out of date as the subject of REA has expanded well beyond these inaugural activities. An up-to-date version has not been published in the unclassified literature, but Table 2 provides insight into how REA has evolved well beyond these inaugural product requirements.

From a Polar Epsilon perspective, collectively, Figure 3 and Table 2 infer why obtaining auxiliary METOC data from RADARSAT ship detection imagery has military applications that extend beyond meteorology, oceanography and ship detection. This pertains to the fact that environmental parameters and features influence the performance of a variety of military sensors, weapons and vessels.

The critical nature of this emerging aspect of NATO METOC operations is becoming apparent with the trend that to an increasing extent environmental information is being requested and retrieved by the deployed warfighter, as opposed to the shore-based specialist [3]. Fulfilling this requirement, however, requires state-of-the-art REA infrastructure. Presently, it is likely that very few navies have such infrastructure.

Table 2. The evolution of tactical military oceanography within NATO, based on information provided by Dr. Peter Ranelli, NATO Undersea Research Centre, La Spezia, Italy. (NATO Unclassified)

TIME FRAME	1980s	1995	2005
Military Era	cold war	regional crisis	expeditionary warfare
Domain	deep water	unknown coastal waters	sea, air, land
METOC Focus	oceanographic & acoustic databases	modelling & GIS	modelling, covert sampling data management & fusion
Response Time	weeks to days	days	days to minutes

Regardless of the fact that NATO's published list of REA product requirements is out of date, this inaugural list identifies the extensive role of boundary conditions (i.e. atmosphere, shore, seafloor and open ocean) in REA. Note that for REA, the open ocean is a boundary. This role is significant not only in terms of required environmental products, but also in terms of applicable technologies. Satellite-based environmental sensors, for example, only observe the surface boundary layer (i.e. surface waters). Thus, many of the requirements identified in Table 1 cannot be fulfilled with spaceborne sensors. Furthermore, as the state of the surface boundary layer is a function of the atmosphere above it and ocean below, this layer cannot be characterized in isolation. This means that in order to be effective in REA and other operational aspects of ocean observing, satellite sensors must be operated in concert with sensors mounted on other platforms.

Indeed, military and civilian requirements identified in Table 1 are so inter-related and so diverse that effective REA and its civilian equivalent require networks of sensors, platforms, data communications, data processing, data storage and distribution architectures, and environmental models - all operating in a synergetic manner. This requirement is the reason why it is likely that

few navies have state-of-the-art REA capabilities, and it is the *raison d'etre* of emerging civilian ocean observing systems.

Satellite sensors occupy a niche within such systems. Although it is a critical niche, Earth observation and other types of environmental sensors are not the only enabling technology for REA. Other civilian technologies have and continue to play key roles, with the Internet, GIS, data communications, Web browsing, modelling and high-performance computing technologies all emerging as critical elements of operational REA and civilian ocean observing.

It has also been observed that recent advancements in sensor design are not the primary driving force behind REA [3]. It is the emergence and integration of these other enabling technologies combined with advancements in platform design. There will always be a requirement for innovation in sensor design in REA and ocean observing in general, but presently, the field is infrastructure limited.

3.3 Spaceborne sensors

As a platform for ocean observing, a satellite has four governing advantages over other platforms: (i) provides a synoptic view, (ii) operates in remote regions, (iii) can be used covertly and (iv) observes all areas with the same sensor. Thus, to gain insight into whether a satellite platform is required for a given monitoring or surveillance application, one considers whether the requirement involves very large areas, remote areas, or covert operations. Monitoring winds, waves, currents or ship traffic in the approaches to Halifax harbour, for example, does not require a satellite platform. Such monitoring can be conducted with substantially less expensive *in situ* and shore-based technologies, and with much greater accuracy and confidence.

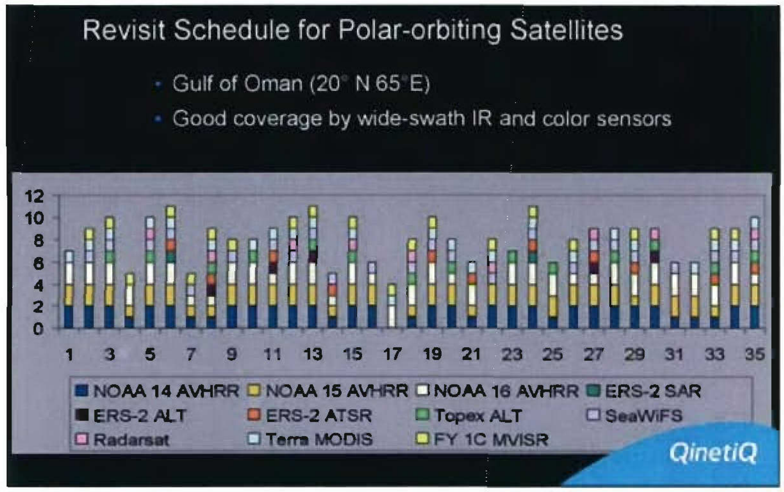
This example highlights the fact that definition of the spaceborne niche in ocean observing requires consideration of the other four types of platforms – aircraft, surface vessels and platforms, sub-surface vessels and platforms and shore-based installations. A satellite's synoptic view, for example, facilitates investigation of relatively large areas and environmental processes, but sensors mounted on airborne and shore-based platforms also provide synoptic views. Similarly, there are several types of *in situ* platforms that operate covertly, thus, neither is this advantage unique to satellites. Note that the key issue here is the platform, not the sensor.

Presently, the fields of REA and civilian ocean observing are infrastructure limited. The platform issue is but one aspect of this. These limitations have been underestimated in the past, with the result that although a given satellite sensor has been shown to detect a certain parameter or feature, it has not been able to fulfill the corresponding operational application.

The platform aspect of this limitation is exemplified in Figure 4 by the British defence company QinetiQ. The figure demonstrates that in the Gulf of Oman, available thermal IR satellite sensors provide several images of the region per day, almost every day. Similarly, existing multispectral sensors provide approximately daily coverage. Existing civilian synthetic aperture radar (SAR) sensors (e.g. RADARSAT-1), on the other hand, provide a total of 11 images during the 35 day demonstration period, about once every three days. This is insufficient for operational weather and ocean forecasting in littoral waters and this has influenced the perceived operational value of SAR's METOC capabilities. All but two of these radar images are provided by RADARSAT-1, which has an effective revisit time of about four days at the latitude used in this example. Note

that this figure precludes the availability of Envisat SAR and Aqua MODIS data, however, the overall point of the figure has not changed.

Figure 4. Gulf of Oman (20° N 65° E) 35-day revisit schedule for aquatic, polar-orbiting, Earth-observation satellites. Graph provided by and reprinted with the permission of N. Stapleton, QinetiQ, UK. The x-axis label is *Day Number In 35 Day Period*. The y axis indicates total number of satellite images.



Infrastructure limitations, which affect both the civilian and military communities, are the reason why Polar Epsilon will benefit from cooperative usage of civilian ocean observing systems. These systems include platforms and sensors that do not, for example, suffer from certain inherent limitations of satellites, including their restriction to viewing surface waters and their separation from the ocean by the atmosphere.

3.3.1 Earth-observation satellites

Table 3 summarizes civilian and certain military Earth-observation satellites that are capable of viewing Canada's Arctic and detecting METOC parameters or features. Table 3a lists all relevant multispectral and thermal IR sensors whereas 3b lists all of the relevant microwave sensors. The tables are limited to polar-orbiting satellites that are functioning as of March 2005. Recent academic treatises and descriptions of these sensors are available [e.g. 6, 7] and the Internet provides an additional comprehensive source of information. The main Web sites for all sensors listed in Table 3, for example, can be accessed via www.oeatech.com.

In addition to identifying the satellites and sensors, Table 3 lists METOC parameters and features that can be detected with these sensors, and it cross references the two. The table identifies an application as belonging to one of two categories. If the application of a given satellite sensor is reasonably well founded, it is identified with a green ball. If the application is under development, or has limitations that prevent it from being the optimal type of satellite sensor, it is identified with a grey ball. In this regard, note that although MODIS is listed as being well suited for monitoring turbidity and surface temperature, RADARSAT has a grey ball pertaining to the detection of surface wind vectors, current vectors and surface waves. In this case, the devil is in the details, as discussed in subsequent sections of this report.

As stated previously, there are significant differences between a sensor's ability to detect a METOC parameter or feature and a satellite program's ability to fulfill operational requirements.

Table 3 provides partial insight into this by including information pertaining to repeat times (i.e. how often the sensor effectively revisits a given location), whether the data are available in near-real time (defined herein as within two hours of satellite overpass), and so on.

Table 3. (a) Multispectral and thermal IR and (b) microwave satellite sensors used to detect marine environmental parameters and features. A green ball indicates the application is reasonably-well founded. A grey ball indicates the sensor is not optimal but merits consideration.

[The tables include all civilian polar-orbiting environmental sensors that sense at mid-latitudes and have a spatial resolution < 70 km, except certain Asian research sensors having restricted coverage and distribution. Where a satellite program involves a series of satellites, the table only lists relevant sensors mounted on the latest satellite in the series. 1. Sensor type (C)ommercial, (Met)eorology, (Mil)itary or (R&D)research/development. 2. The sensor's repeat time refers to either the satellite's orbit revisit time or the sensor's effective revisit time (identified with a "~") at mid-latitudes. Revisit time varies with latitude and sensor configuration. 3. In this table, near-real time data are those delivered to the user within two hours of satellite overpass.]

(a)

SATELLITE	ORBVIEW 3	QUICKBIRD	IKONOS	SPOT	LANDSAT & EO	SAC-C	OCEANSAT	ORBVIEW 2	ENVISAT	TERRA & AQUA	POES	ENVISAT
SENSOR	multispectral	multispectral	multispectral	HRG	ETM & ALI	MMRS	OCM	SEAWIFS	MERIS	MODIS	AVHRR	ATSR
type[1]	C	C	C	C	R&D	R&D	R&D	C	R&D	R&D	Met	R&D
revisit time (days)[2]	~3	~3	~3	~2	16	9	~2	~1	~3	~1	~0.25	~3
near-real time[3]	no	no	no	no	no	no	yes	yes	no	yes	yes	no
pixel size (m)	4	2.5	4	10	30 & 30	175/350	360	1100/4000	300/1200	250/1000	1100/4000	1000
country or agency	USA	USA	USA	France	USA	Argentina	India	USA	ESA	USA	USA	UK
Coastal Flooding	🟢	🟢	🟢	🟢	🟢	⚫						
Fronts/Eddies (biological)							🟢	🟢	🟢	🟢		
Fronts/Eddies (thermal)					⚫					🟢	🟢	🟢
Ice	⚫	⚫	⚫	⚫	⚫	⚫	⚫	⚫	⚫	⚫	⚫	⚫
Surface Temperature					⚫					🟢	🟢	🟢
Turbidity	⚫	⚫	⚫	⚫	⚫	⚫	🟢	🟢	🟢	🟢		
Beach Vegetation	🟢	🟢	🟢	🟢	🟢	⚫						
Water Quality (biological)							🟢	🟢	🟢	🟢		

(b)

SATELLITE	TOPEX / POSEIDON	JASON	GFO	ENVISAT	RADARSAT	ENVISAT	DMSP	AQUA	QUICKSCAT	ERS
SENSOR	altimeter	altimeter	altimeter	altimeter	SAR	SAR	SSM/I	AMSR	Seawinds	scatterometer
type[1]	R&D	R&D	Mil	R&D	C	R&D	Mil	R&D	R&D	R&D
revisit time (days)[2]	10	10	17	35	~3 to ~5	~3 to ~5	~0.25	~2	~1-2	~4
near-real time[3]	no	no	no	no	yes	yes	yes	eventually	yes	no
pixel size (m)					10 to 100	30 to 1000	25000	24km to 56km	25000	25000
country or agency	France/USA	France/USA	USA	ESA	Canada	ESA	USA	Japan/USA	USA	ESA
Coastal Flooding					🟢	🟢				
Currents (geostrophic)	🟢	🟢	🟢	🟢						
Eddies (mesoscale)	🟢	🟢	🟢	🟢	⚫	⚫				
Ice	⚫	⚫	⚫	⚫	🟢	🟢	⚫	⚫	⚫	⚫
Waves (surface)	⚫	⚫	⚫	⚫	⚫	⚫				
Surface Slicks					🟢	🟢				
Surface Temperature							⚫	⚫		
Waves (internal)					⚫	⚫				
Wind (vectors)	⚫	⚫	⚫	⚫	⚫	⚫	⚫	⚫	🟢	🟢

3.3.2 Practical application to REA

Many of the Earth-observation programs listed in Table 3 are research and development programs that have limited operational utility for REA and, as stated previously, several REA requirements cannot be fulfilled by any Earth-observation satellite. This is demonstrated in Table 4, which identifies the Earth-observation programs listed in Table 3 that operate in near-real time and address or partially address at least one METOC requirement for defence, security and enforcement, as listed in Table 1.

We particularly note the fact that the MODIS sensor on the Terra satellite is not included in Table 4 because although the Terra satellite is still in operation, the ocean colour channels of MODIS / Terra have experienced a technical failure that essentially eliminates their practical application. Thus, all further discussion of the MODIS sensor in this report refers specifically to the MODIS sensor on NASA's Aqua satellite and to the 250-500 m "true colour" channels of MODIS / Terra, the latter of which were originally designed for cloud top and terrestrial applications.

RADARSAT is not listed in Table 4 as being capable of detecting surface wind vectors (i.e. wind speed and direction). This is because presently RADARSAT is capable of providing wind speed but not direction on an operational basis. As indicated in Table 4, there are a multitude of civilian Earth-observation sensors capable of providing wind speed information. Thus, the unique aspect of RADARSAT in this case is not the fact that it provides wind speed information, but that it does so at the same time and location that RADARSAT is being used for ship, oil and possibly submarine detection, and it does so with finer spatial resolution than can be obtained with scatterometers, altimeters and available passive microwave sensors. Recognizing these details is critical to understanding RADARSAT's potential for operational METOC applications.

Table 4 indicates that another high-priority requirement identified in Table 1 - surface current vectors - cannot be fulfilled by any spaceborne sensor. However, aspects of surface currents can be detected with satellite sensors, as listed in the table. Note that if the satellite image does not include a land feature, and the winds are not light to moderate, spaceborne SAR can only provide surface-current gradients [8]. Even in the presence of land and light to moderate winds, RADARSAT only provides current radials, not current vectors. A surface current radial is the component of the surface current that is moving directly away from or toward the sensor.

Note that Table 4 does not list littoral bathymetry as a requirement that is being fulfilled operationally with spaceborne sensors. Although there is extensive literature on this subject and spaceborne sensors provide practical bathymetric information for oceanic waters, the existing optimal satellite sensor (i.e. altimeter) does not have the resolution required to fulfill littoral requirements for bathymetric data [9]. This situation is evolving and therefore may change.

Altimeters also play a central role in operational determination of oceanic (i.e. blue water) tides and are providing information pertaining to mesoscale eddies and geostrophic currents such as the Gulf Stream [10]. However, altimeter products that are used for mesoscale circulation and for operational current purposes are provided two to seven days after satellite overpass (personal communication, Aviso User Services - www.aviso.oceanobs.com). This is sufficient for blue water operations, for tracking mesoscale eddies in all waters and for constraining the open ocean boundary in nested littoral forecasting models, as recognized in Table 4 ("Definition of Ocean Boundary"), but is well outside Table 4's definition of near-real time (i.e. within two hours of satellite overpass) and therefore well outside the operational needs of Polar Epsilon.

By strict definition, altimeters should not be included in Table 4's "surface wave spectrum" section. Users can obtain all of the METOC products that can be extracted from altimeters via the Internet (www.aviso.oceanobs.com), but the significant wave height product derived from altimeters that is made available to civilians is delivered three hours after satellite overpass (personal communication, Aviso User Services - www.aviso.oceanobs.com). This is longer than the two hour definition of near-real time used in this report, but the difference between the two is such that it would be misleading not to include altimeters in this section of the table.

Table 4. Civilian METOC satellite capabilities that are applicable to NATO REA operations.

REA Requirement	Satellite Capability	Satellite Sensor Type	Available Satellites	Satellite Owners	Application of Capability to NATO Operations
surface wind vectors	surface wind vectors	scatterometer	Quickscat	USA	all littoral naval operations
	wind speed only	altimeter, SAR passive microwave	Jason, GFO, T/P, DMSP Radarsat, Envisat	USA, France Canada, ESA	ship detection wake detection ASW
surface current vectors	surface current radials - limited to strong currents near land in light to moderate winds	SAR	Radarsat, Envisat	Canada, ESA	?
	gradient of surface current radials	SAR	Radarsat, Envisat	Canada, ESA	?
	motion of mesoscale fronts and eddies	altimeter, thermal IR, multispectral	Jason, Envisat, T/P, GFO, POES, Oceansat Aqua, Orbview 2	USA, France ESA, India	navigation
surface wave spectrum	swell, wind sea with azimuth cut-off	SAR	Radarsat, Envisat	Canada, ESA	?
	significant wave height	altimeter	Jason, GFO, T/P Envisat	USA, France, ESA	all littoral naval operations
surface temperature	surface temperature	thermal IR	POES, Aqua	USA	all littoral naval operations
sea ice	sea ice	SAR	Radarsat, Envisat	Canada, ESA	navigation
turbidity	turbidity	multispectral	Orbview 2 Aqua, Oceansat	USA, India	ASW, MCM, SubOps amphibious Ops
internal waves	internal waves in light to moderate winds	SAR	Radarsat, Envisat	Canada, ESA	ASW, SubOps amphibious Ops
	internal waves in sunglint	multispectral	Orbview 2, Aqua, Oceansat	USA, India	ASW, SubOps amphibious Ops
define surface boundary for models	oceanic surface boundary	scatterometer altimeter, thermal IR	Quickscat, GFO, Jason, T/P, Envisat, Aqua, POES	USA, France ESA	littoral modelling
	littoral surface boundary	scatterometer thermal IR	Quickscat, Aqua, POES	USA, France	littoral modelling
fronts, eddies	fronts, eddies	altimeter, thermal IR, multispectral, SAR	Jason, Envisat, T/P, GFO, POES, Oceansat, Aqua, Orbview 2, Radarsat	USA, France, ESA India, Canada	ASW, SubOps navigation

Similarly, the SAR on ENVISAT is included in Table 4 even though it is highly unlikely that Polar Epsilon will receive Envisat SAR data within two hours of satellite overpass. The Canadian Ice Service is implementing infrastructure that will permit it to obtain processed Envisat SAR imagery within three to four hours of satellite overpass, via a private service provider and Canada

Centre for Remote Sensing reception facilities located in Gatineau and Prince Albert. A user could conceivably install their own on-site reception and processing capability that may very well achieve the two-hour reception benchmark imposed in this report, but this would require a separate and exceptional licensing agreement with the European Space Agency. (Bruce Ramsay, BRR Consulting, personal communication).

4. Obtaining METOC information with RADARSAT

This section summarizes METOC opportunities from civilian spaceborne synthetic aperture radar (SAR) image data, focussing on RADARSAT. These civilian SAR systems are usually characterized by low to moderate spatial resolution, are radiometrically calibrated, and provide image data on an operational schedule.

4.1 Winds, waves, currents and features

Access to wind, wave and surface current parameters provides the opportunity to assess the environment in which the SAR observation was made, which may be important information in its own right, but also permits the opportunity to predict target detection performance. This is relevant since ships are usually detected as bright point-like targets against the ocean clutter background; the clutter background is primarily a consequence of the local wind conditions. Waves and currents also tend to modulate the background clutter. This increases the length of the probability density function tail, which is required for setting constant false alarm rate thresholds in practical ship detection systems. Oil slicks are usually detected as local suppressions in the ocean clutter background.

By using marine information estimated from the SAR image, it may be possible to answer the following types of questions: "For these actual wind conditions, what size of ship should we expect to be able to detect?"; and "For these actual wind conditions, should we expect to be able to detect an oil spill?" Strategically, this could help to improve the end-user's confidence in the SAR-derived information of interest (e.g. the set of identified candidate ship targets).

4.1.1 Winds

Commercial spaceborne SAR systems are always radiometrically calibrated. Therefore, the normalized radar cross-section, for the particular acquisition wavelength and polarization, is routinely available from the image data. The normalized radar cross section is a measure of the surface roughness at the Bragg scattering scale, a few centimetres for C-band SAR, and is primarily governed by the local wind conditions.

The normalized radar cross-section can be used to estimate the wind speed at the ocean surface to high resolution (1 km or better, as compared to resolutions of 25 km for a spaceborne scatterometer). By using the principle of wind scatterometry, a semi-empirical model function may be used to estimate the surface wind speed from the observed normalized radar cross-section, the local incidence angle, and the relative wind direction. The normalized radar cross-section may be estimated directly from the SAR image; the local incidence angle comes from the geometry; it remains a challenge to estimate the wind direction from SAR image data, but there are often useful indicators in the imagery, or external sources of wind direction can be used in an operational setting.

The wind direction can be estimated from the SAR data alone for roughly one half of the open ocean cases. The key wind direction indicators are image streaks caused by boundary layer rolls that form under unstable atmospheric conditions, and wind shadows that appear in the coastal zone (i.e. dark shadows on the lee side of islands, or wakes that originate on headlands). The boundary layer rolls have a 180° wind direction ambiguity, however, the SAR-derived Doppler

centroid anomaly, which is discussed in the subsequent section on surface currents, can be used to resolve this directional ambiguity.

For other cases, possible sources of wind direction are operational buoys, high-resolution numerical weather prediction models, and operational scatterometers. A blended approach, for example, combining SAR-derived information with a first guess from a numerical weather prediction model, should provide reliable wind directions.

Based upon comparisons with operational buoy measurements, it has been shown that the wind speed can be estimated to better than 2 m/s from ERS-1/2 and RADARSAT-1 SAR images at a spatial resolution of roughly 1 km [11]. Based upon comparisons with NASA's Quickscat scatterometer it has been shown that the wind speed can be estimated to within roughly 1.5 m/s from RADARSAT-1 SAR images [12].

A SAR-derived, high-resolution wind field can be used to advance Polar Epsilon's ship detection capabilities. If the actual wind speed is known, it is possible to use a model to estimate the scale of ship that should be detectable for the actual conditions at the time of data acquisition. For example, the Vachon et al. ship detection model [13] relates the wind speed, the wind direction, and the clutter statistics to the minimum detectable ship size. This expected performance baseline could be used to better understand candidate ships detected in SAR imagery (e.g. for the observed conditions, the minimum detected ship size might be 50 m, which would explain why smaller vessels were not detected). Whitehouse recommends this routine use of SAR-derived wind speed [2].

A SAR-derived, high-resolution wind field can also be used to advance knowledge of ambient noise at the surface boundary layer, in support of improved sonar sensor performance for anti-submarine warfare (ASW). Definition of the acoustic environment requires, among other parameters, wind speed and a shipping density parameter, both of which can be derived from the SAR image data [14].

Much of the ongoing work pertaining to extraction of meteorological features (e.g. polar lows) from RADARSAT imagery focuses on detecting extreme meteorological events, which involve high to extreme wind conditions (e.g. storms, gales and hurricanes). Detecting extreme meteorological events is of little value to the Polar Epsilon project because its ship and oil detection programs pertain to environments experiencing low to moderate wind speeds – up to Sea State 5 (approximately 12 m/s). At such speeds, oceanographic features, such as fronts, eddies, plumes, surface slicks and internal waves dominate the feature image, although meterological features that permit determination of wind direction may be present.

4.1.2 Waves

Striations related to surface waves are often visible in SAR imagery of the ocean surface. In fact, SAR is the only spaceborne sensor that permits observation of the directional wave conditions. The surface waves are rendered visible through sensing of the differential wave orbital velocity in a process that is known as velocity bunching. Unfortunately, velocity bunching is highly non-linear, often making it difficult to relate the wave patterns seen in a SAR image to the actual wave conditions on the ocean surface. The imaging process becomes more nonlinear for steeper (i.e. higher and/or shorter) wave conditions. The imaging non-linearity is exacerbated for SAR platforms that have a large range-to-velocity ratio (R/V). For polar orbiting SARs such as RADARSAT, $R/V > 115$ s, which is very large and limits the ability to reliably image the directional wave spectrum.

The imaging nonlinearity expresses itself through the introduction of an azimuth cut-off in the observed image spectrum. That is, waves that have an azimuth component that is shorter than the cut-off wavelength cannot be imaged. As such, SAR images of ocean swell have the best fidelity; SAR images of wind seas could suffer from imaging distortions.

Nonlinear inversion schemes, usually involving an iterative procedure that minimizes a cost function, have recently improved [15], especially if multiple polarizations are available [16]. The inversions permit estimation of the dominant wavelength and direction, as well as the significant wave height, subject to the azimuth cut-off constraint that is caused by velocity bunching non-linearity.

On the other hand, the azimuth cut-off wavelength, which can be measured directly from the SAR image spectrum (independent of carrying out an inversion to a wave spectrum), is readily available from SAR image data. The azimuth cut-off can be interpreted as a scene coherence time, which in turn can also be used to provide an estimate of the surface wind and wave conditions [17].

4.1.3 Currents

Bulk movement in the radial (i.e. range) direction of the surface being imaged by SAR introduces a Doppler shift of the received signal. The surface movement can be caused by the local surface current conditions and by wind-induced surface drift.

The Doppler centroid is a measure of the range-dependent, azimuth-pointing angle of the SAR antenna. The azimuth pointing is a function of the geometry of the data acquisition, the Doppler contribution from Earth rotation (a function of latitude), and the target motion. The antenna pointing angle must be accurately known in order to form the SAR image, so is routinely estimated in the SAR processor.

It has been shown that the Doppler centroid can be estimated to within 5 Hz on a spatial grid of 1 km by 1 km. [18] By comparing the observed Doppler centroid with the expected Doppler centroid (based upon the acquisition geometry), the Doppler centroid anomaly can be calculated. This can then be related to the motion of the ocean surface, specifically, the effects of components of the local surface current conditions, and wind-induced surface drift.

This anomaly can be used to resolve the radial component of the surface current speed to within 0.2 to 0.3 m/s [20, 19] but only if there is a zero velocity reference (i.e. land) in the image. If there is not a zero velocity reference in the image then the Doppler analysis does not provide absolute surface current speed but can be used to estimate the gradient of the mean surface current radial. In both cases, the Doppler analysis method works best for larger currents and only if the wind speed is not too high, in which case the Doppler anomaly would be dominated by wind-induced drift. The derived current speed component is limited to a spatial resolution of approximately 1 km. Regardless of whether the image includes a zero velocity reference, this technique does not provide surface current vectors (i.e. current speed and direction).

Recent results indicate that for higher wind speeds, the Doppler anomaly can also be used to resolve the 180° ambiguity in SAR-derived wind direction and to estimate the wind speed [19].

4.1.4 Features

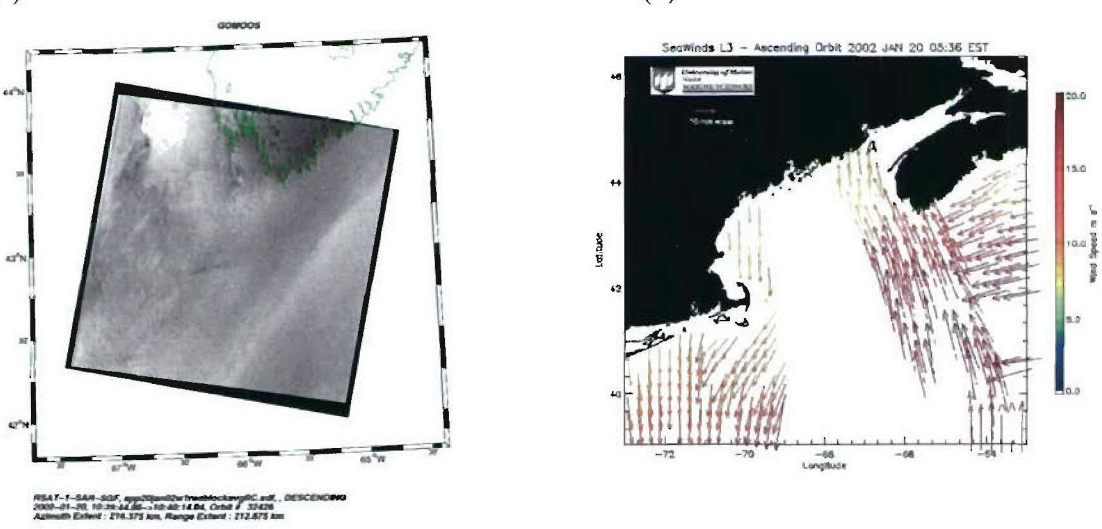
As stated previously, a SAR image of the ocean surface is a spatial mapping of the ocean surface roughness at the Bragg scale, a few centimetres for C-band SAR. SAR can image any physical process that modulates the roughness at this scale. The dominant effect is from the wind: the higher the wind, the rougher the surface, and the brighter the SAR image. For higher wind speeds (nominally 10 m/s and above), the image is dominated by the wind and the image can contain patterns related to features in the marine atmospheric boundary such as gravity (i.e. atmospheric internal) waves [20], wakes [21], and mesoscale storms such as polar lows [22] and hurricanes [23]. For lower wind speeds, it is possible to see the effects of oceanographic phenomena on the Bragg-scale roughness and patterns related to the upper ocean circulation [24]. The shape and orientation of image structures related to these phenomena can provide insight to the environmental conditions at the air-sea interface.

Image structures can be measured both interactively and automatically. A useful automatic approach is via wavelet analysis, which permits the detection of image boundaries and textures, depending upon the choice of wavelet basis function. Wavelets offer the advantage of automatically adapting to the scales of the structures that are present [25]. Furthermore, special wavelets can be defined to optimize the detection of certain types of structures.

It is beyond the scope of this report to fully catalogue the nature of the structures that are visible in SAR ocean images. We provide examples in Figures 5 and 6, followed by a brief summary of some structures of interest and the environmental information that the structure could provide.

Figure 5. (a) RADARSAT-1 Wide Mode SAR Image of the Gulf of Maine acquired 30 Jan. 2002. The wind is higher in the eastern region and lower in the western region of the image. The bright band of higher wind in the east could be a meteorological front - see confirmation of this in corresponding Quickscat image of same area and similar time (5b). The linear features in the west are related to the surface currents.

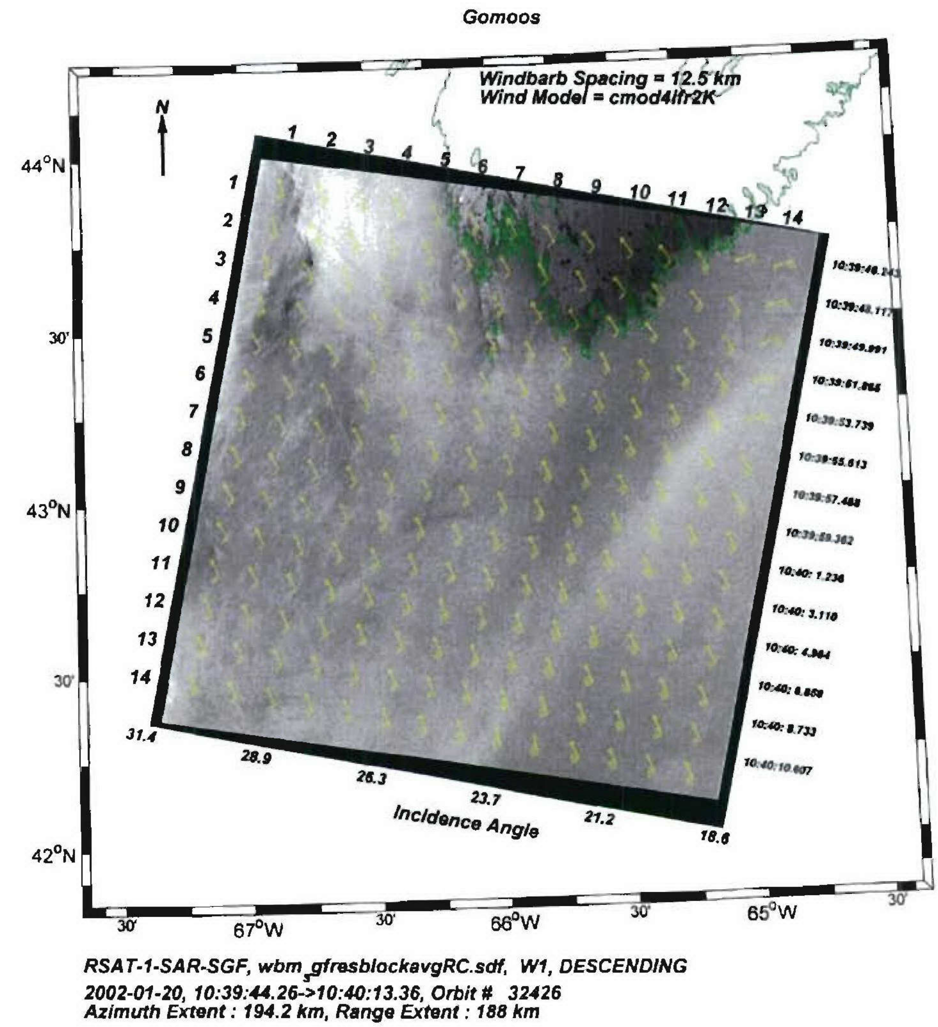
(a) (b)



1. Atmospheric structures (normally observed for higher wind conditions):

a. Boundary layer rolls – measurement of their orientation is the main approach to SAR image derived wind direction, with a 180° direction ambiguity;
b. Wind shadows and wakes from land – measurement of their orientation is a secondary approach to wind direction, especially in the coastal zone, probably requiring an interactive analysis and resulting in no ambiguity in wind direction;
c. Convective cells – their scale and orientation provides information on the stability of the marine atmospheric boundary layer;
d. Gravity (i.e. atmospheric internal) waves and wakes – the presence of stable layers in the marine atmospheric boundary layer;
e. Mesoscale storms – high winds and severe precipitation.

Figure 6. Wind vectors extracted from the RADARSAT scene shown in Figure 5 (a). The scatterometer wind vectors shown in Figure 5(b) were used to initialize wind direction. Note that there is roughly 1.5 hrs between the RADARSAT and Quickscat passes, which would lead to mis-registration of features, especially for dynamic features such as meteorological fronts. Evidently, the bright diagonal band in the image that runs from upper-right to lower-mid region of the image is a meteorological front.



2. Oceanic structures (normally observed for lower wind conditions):
    a. Natural slicks – a cause of false oil slick detection and a tracer of surface water movement;
    b. Anthropogenic slicks – an indicator of shipping activity (e.g., fishing, bilge pumping, etc.) and offshore oil spills;
    c. Current shear, ocean fronts and eddies – water mass boundaries, which have implications for ship detection and sound propagation;
    d. Internal waves – the presence of stable layers in the upper ocean, which has implications for sound propagation and perhaps submarine detection.

4.2 Practical issues

The processing of SAR images to derive METOC features and parameters is no longer considered to be computer intensive. It is feasible to implement a near-real time processing capability on a modern high-end PC. Parameters such as the wind speed could be derived operationally from the image with very short turnaround, especially if a numerical weather prediction model wind field is available to provide a first guess wind direction. More computer intensive operations such as estimation of wind direction and extraction of METOC features might require several minutes of processing time per image.

There are several methods of estimating the wind direction from a SAR image. A practical approach would be to run two or three of these methods, and then to produce a blended wind direction field that includes the first-guess model directions and the SAR-derived directions. It will probably require a few minutes of operator interaction to verify and adjust the SAR-derived and blended (i.e. combined model and SAR-derived) wind direction fields, and to take into consideration other wind direction cues such as wind vectors from Quickscat and wind shadows if land is present in the image. The wind speed retrieval may have to be re-run at this point.

Similarly, operator interaction may be required to verify extracted METOC features, especially to better classify and verify their origin.

Although the noted parameters can be extracted from SAR imagery in an automated fashion, there are issues that can only be resolved through operator inspection, adjustment, and verification of derived results. A training course could be designed to develop the necessary operator insight. The course could be delivered over a timeframe of a few days, with a focus on discussing real data in the local context, which the local specialist would be familiar with.

5. Obtaining METOC information with MODIS

MODIS is one of a suite of instruments mounted on NASA's presently operational EOS series of polar orbiting satellites. There are two of these satellites, referred to variously as Terra and Aqua or EOS AM and EOS PM, where the AM and PM refer to their equatorial crossing times of 10:30 and 13:30, respectively.[2] The overall purpose of these instruments is to make synoptic, repetitive, quantitative measurements of terrestrial, atmospheric and oceanic bio-geophysical processes and patterns. For ocean operations, the quantities of foremost interest are likely to be those pertaining to ocean color and sea surface temperature (SST).

Both EOS satellites are in a sun-synchronous low Earth orbit (~700 km). This, plus the swath width (2,330 km) of the MODIS radiometer provide complete Earth coverage every two days, with coverage at least every 24 hours at mid and higher latitudes. MODIS has 36 co-registered channels, with spatial resolutions of 250 m for the first two channels (1,2), 500 m for the next five channels (3-7), and 1,000 m for the remaining channels (8-36). Data broadcast rate is 10 Mbps with a 12 bit quantization, requiring a ~3 m antenna operating in X-Band to receive the transmission. More complete specifications of the instrument, channel specifications and data structures are made available on the NASA web site (http://modis.gsfc.nasa.gov).

NASA provides a suite of "community-approved" standard products derived from MODIS data, using some of the more widely accepted and tested algorithms (See Table 5). Included in these products are the atmospherically corrected quantities in each of the visible channels, from which a host of additional "research" products can be derived, using algorithms from the scientific literature. A list of example additional research products produced by the MODIS science team is given in Table 6, along with the NASA product code used to specify that product. Details on each of these are also available on the NASA web site.

It should be noted that the reduced list of "community-approved" products generated by NASA are primarily a result of 1) an effort to streamline and reduce the number of products produced operationally by NASA to reduce data volumes, and 2) an effort to disseminate those products receiving wide global usage and which perform well in a global least-squared error sense. At specific times / locations, various research products may perform better than these "community-approved" NASA products. In addition, many additional, potentially useful, data products from MODIS have been presented at science meetings and/or on the web, but remain untested in NE Atlantic coastal waters and are not yet in the peer-reviewed literature.

From a naval perspective, the application of ocean colour to operations pertains to submarine operations, antisubmarine warfare, mine countermeasures and amphibious warfare. It relates largely to the opacity of the water column and its influence upon detection of submarines, mines and special forces. To a certain extent it also pertains to bioluminescence, which may also influence detection.

MARLANT MetOc is in the process of acquiring a MODIS licence and technical training, and expects to make products such as ocean color, turbidity and chlorophyll-A concentrations available to the east and west coast navies by summer 2005. [personal communication, LCdr. Wayne Renaud, SSO, MARLANT MetOc]

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[2] As discussed in Section 3.3, the ocean colour channels of MODIS / Terra have experienced a technical failure. Data from these channels are no longer being processed by NASA.

Table 5. Accepted and tested MODIS algorithms.

Geophysical Parameter	Description	Units
nLw_412	Normalized water-leaving radiance at 412 nm	mW·cm-2·µm-2·sr-2
nLw_443	Normalized water-leaving radiance at 443 nm	mW·cm-2·µm-2·sr-2
nLw_488	Normalized water-leaving radiance at 488 nm	mW·cm-2·µm-2·sr-2
nLw_531	Normalized water-leaving radiance at 531 nm	mW·cm-2·µm-2·sr-2
nLw_551	Normalized water-leaving radiance at 551 nm	mW·cm-2·µm-2·sr-2
nLw_667	Normalized water-leaving radiance at 667 nm	mW·cm-2·µm-2·sr-2
Tau_869	Aerosol optical thickness at 869 nm	dimensionless
Eps_78	Epsilon of aerosol correction at 748 and 869 nm	dimensionless
Chlor_a OC3	Chlorophyll a concentration	mg·m-3
K490	Diffuse attenuation coefficient at 490nm	m-1
Angs_531	Angstrom coefficient, 531-869 nm	dimensionless
SST	Daytime Sea Surface Temperature	degrees Celsius

Table 6. Example research products produced by the MODIS science team.

Research Product	Description
MOD 19	Pigment Concentration
MOD 20	Chlorophyll Fluorescence
MOD 22	Photosynthetically Available Radiation (PAR)
MOD 23	Suspended-Solids Concentration
MOD 24	Organic Matter Concentration
MOD 25	Coccolith Concentration
MOD 27	Ocean Primary Productivity
MOD 31	Phycoerythrin Concentration
MOD 36	Total Absorption Coefficient
MOD 37	Ocean Aerosol Properties
MOD 39	Clear Water Epsilon

A comprehensive assessment of Canadian Forces requirements for environmental products derived from ocean colour data is not available in the unclassified literature, but comments

provided in a 2002 / 2003 assessment of Canadian Forces submarine operations requirements for environmental data are relevant [2].

From a METOC perspective, the 3-D sound velocity profile is of highest priority to submarine operations. Sound velocity in the water column depends on several environmental factors in littoral waters, but efforts generally focus on determining water density, which in the marine environment is mostly a function of water salinity and temperature. Bottom properties and ambient noise may also influence the performance of relevant sensors, the latter of which is influenced by surface winds. The presence of marine mammals is also relevant.

The next two highest priority requirements are for water currents, both surface and subsurface, and water turbidity. Both current and turbidity information are required in near-real time, but for different reasons. Water currents are required in support of submarine navigation, whereas water turbidity information is required to avoid detection of vessels and deployed divers (e.g. during amphibious operations).

Another environmental assessment requirement is knowledge of the presence of bioluminescent plankton. This is required to avoid detection when at the surface or at periscope depth.

Another unique aspect of submarine operations is that once deployed, they are covert 24/7 and therefore do not wish to transmit. This means that in order to send environmental assessments to deployed submarines, a broadcast transmission technique is required. Such techniques tend to be bandwidth limited and therefore involve relatively small data files, or make extensive use of data compression techniques. To rectify this shortcoming, MARLANT MetOc has proposed that its current analogue meteorological broadcast be converted to a digital meteorological and oceanographic broadcast so as to have the necessary bandwidth to transmit oceanographic products to the submarine community, including SSTs, OFAs, MODIS products and ocean modelling products. [personal communication, LCdr. Wayne Renaud, SSO, MARLANT MetOc]

5.1 Turbidity, Colour, Temperature and Features

Measurements of water leaving radiance in the visible channels of MODIS provide input to algorithms optimized to estimate numerous quantities which determine the surface optical properties of the water column. Most of these algorithms use channel ratio approaches [e.g. 26, 27] and are empirically derived from statistical fits to *in situ* optical or biogeophysical measurements. Quantities of primary interest for which algorithms have been developed include 1) chlorophyll-a concentration, 2) diffuse attenuation coefficient, 3) suspended solids concentration and 4) total absorption coefficient. Each of these products is derived from the 1 km spatial resolution channels and so is produced at 1 km resolution. Details of these algorithms are specified in NASA's Algorithm Theoretical Basis Documents (ATBDs) available on the web at the MODIS site (modis.gsfc.nasa.gov/ data/algorithms.html). Examples of some of these image products for the Gulf of Maine region are shown in Figure 7.

Higher spatial resolution images are available from the first seven channels of MODIS. These high resolution channels are optimized for the high reflectivities used in terrestrial and cloud applications. Water-leaving radiance is substantially less. At present, quantitative algorithms to derive in-water biogeophysical measurements from these data are experimental. However, non-quantitative presentations using both the 250 m and the 500 m resolution data reveal a wealth of oceanic patterns potentially useful to marine operations and SAR data interpretation. The elevated

reflectances in coastal waters resulting from suspended sediments and increased phytoplankton concentrations allow these data to provide image estimates of water turbidity in the coastal zone. Offshore in clear oceanic water, reflectivities are low and information in these channels is restricted to patterns resulting from sun glint rather than in-water properties. Coastal relative turbidity patterns track coastal circulation dynamics, coastal frontal zones, high concentration phytoplankton blooms and river discharge plumes. Larger ships and/or their wake patterns are evident in these images. Slicks and other surface expressions of roughness pattern are often evident in modulations of the sun-glint pattern. Extensive internal wave packets are often evident. All of these features provide information to both marine operations and the utility of SAR data in a target region. Examples of one type of higher resolution MODIS image product (true-colour 250 m images) are shown in Figure 8.

In optically shallow water (depths where the bottom is visible from above), some aspects of bathymetric features may be distinguished. Spatial resolution of these features is limited to that of the sensor, and the wide spectral channels of current spaceborne sensors (e.g. MODIS) restrict the categories of bottom type determination. However, distinguishing between broad, major bottom types such as sand, grass beds, other bottom vegetation and changes in depth is often possible. Accurate quantitative estimates require ancillary optical information. Primary issues determining the utility of the data are the actual water depth, the clarity of the overlying water column and distinguishing between bottom reflectance and suspended sediment. An overview of these topics is presented by Philpot et al. [28].

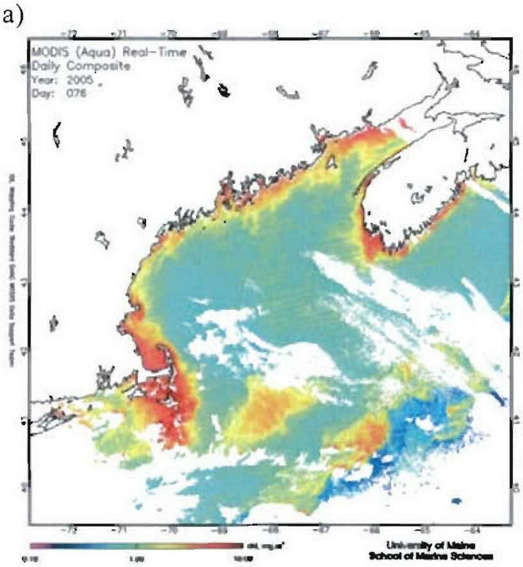
In summary, existing products that may be derived from MODIS data include: (1) from chlorophyll concentrations - concentration of phytoplankton, likelihood of encountering bio-luminescence, optical clarity of the water, water mass boundaries, frontal zones, advective features (from sequential images); (2) from extinction coefficient - optical clarity of the water, light penetration; (3) from suspended sediments / turbidity - clarity, frontal zones, water mass boundaries, river discharge plumes; (4) from the high resolution channels - glint patterns, surface slicks, relative turbidity, larger ship/ship-wakes, coloured river discharges and phytoplankton blooms.

5.1.1 Sea-surface temperature (SST)

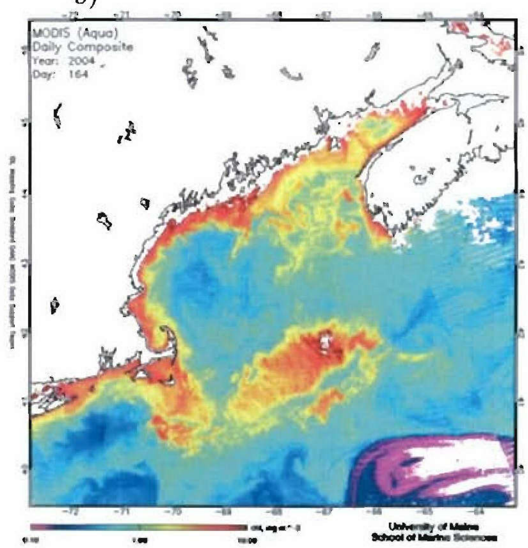
SST estimates temporally concurrent with ocean color products may be produced at a spatial resolution of 1 km on both ascending and descending orbits using radiance measured in the infrared channels. Resulting data are approximately equivalent to SST images produced from NOAA AVHRR data (see Figure 7). Buoy comparisons with both MODIS and AVHRR SST result in RMS uncertainties of ~ 0.5 °K, approaching the error level of the buoy measurements. Qualitatively, imagery from the two sources from the same day reveal very similar SST features on scales of 5+ km. Quantitative differences are primarily a result of: 1) differing time of day of overpass, 2) differing details in the atmospheric correction procedure, 3) any differences in the cloud masking schemes employed by the user for the two data sets and 4) differences in instrument calibration / degradation and NOAA / NASA's ability to track and model these. Beyond this, differences are due to artifacts introduced into the MODIS imagery by instrument engineering issues.

Figure 7. Example 1000 m resolution MODIS Aqua products of the Gulf of Maine / Southwest Nova Scotia showing surface chlorophyll concentrations during a) an early spring period (March 17 2005) and b) a summer period (June 12, 2004). Also shown are c) the associated MODIS-measured SST patterns for June 12, 2004 and d) the NOAA AVHRR SST measured SST patterns for the same day (June 12, 2004). Notes: 1) MODIS images are a composite of one or more orbits covering the study area each day, evident especially in Figure 1b; 2) the AVHRR pass is approximately two hours after the MODIS pass.

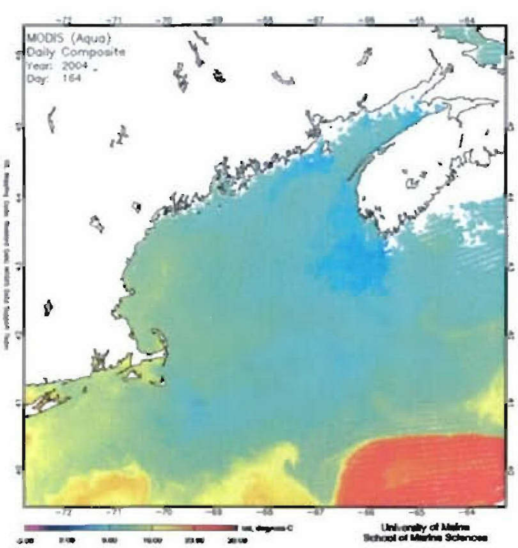
a)



b)



c)



d)

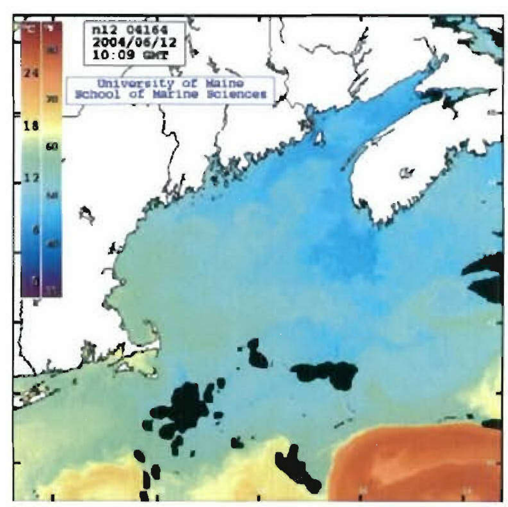
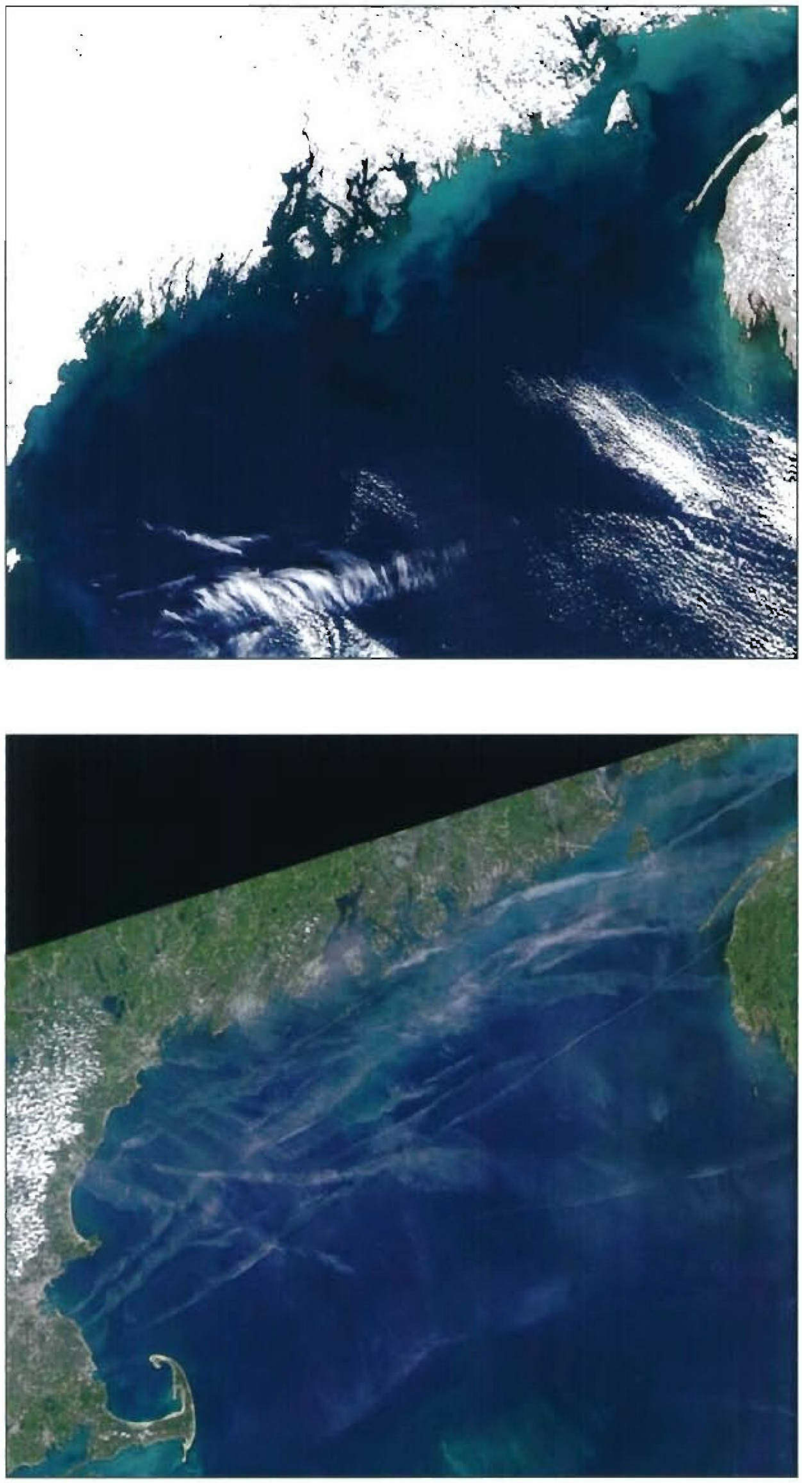


Figure 8. Example 250 m resolution MODIS Aqua "true-colour" products of the Gulf of Maine / Southwest Nova Scotia showing surface turbidity/colour patterns, vapour trails, internal wave patterns and bottom bathymetric features.



Other products that can be derived routinely from these data include climatological and seasonal means, and real-time SST anomalies from mean conditions. SST is a critical input to numerical ocean models (e.g. ocean observatories use real-time satellite data as input of boundary conditions to operational models for ocean forecasting) as well as atmospheric models. Surface thermal patterns can also be resolved, including water mass boundaries, current/eddy locations and edges, frontal zones, tidally mixed regions, river plumes, ice edge boundaries and ice leads. Sequences of imagery may reveal advective fields (i.e. surface currents).

From an operational perspective, the attractions of MODIS SST data are: (1) the availability of 6+ SST images of a target region every 24 hours (four NOAA AVHRR scenes and two MODIS scenes). This provides significantly increased ability to view the ocean through gaps in clouds, deal with moving patchy cloud patterns and image around weather systems. It also offers the potential of resolving smaller time-scale advective displacements using image time series, an important consideration in dynamic regions and on continental shelves; and (2) the availability of exactly coincident SST data and ocean color measurements, providing increased environmental characterization of a region.

5.2 Practical Issues

Unfortunately, the atmosphere contributes about 90% of the signal recorded by spaceborne ocean colour sensors, such as MODIS [29]. The presence of clouds, which represents one aspect of this issue, is arguably the foremost ocean observing limitation for spaceborne sensors like MODIS. This is due to the fact that in coastal waters cloud typically covers 60% of the tropical ocean and 75% of the ocean at mid latitudes [30], which is where much of Canada's sovereign waters reside.

Correcting for this to derive accurate normalized water leaving radiance values is essential and an active research topic in ocean colour remote sensing. This aspect makes extraction of quantitative information on in-water optical properties a challenge. This is primarily a problem for scientific research and time series analysis. Relative differences in radiance within an image still provide valuable information regarding spatial patterns. Improved algorithms, necessitating reprocessing of archived data and updating of algorithms and/or coefficients are published episodically by the community.

In coastal waters, many and varied constituents within the water column contribute to the absorption and backscattering which determine the optical characteristics. These include coloured dissolved substances, various types of sediment and phytoplankton, each of which can vary in composition, optical properties, and concentration in time and space. These aspects further complicate the quantitative extraction of accurate biogeophysical measurements in coastal zone. Not withstanding these issues, relative patterns of turbidity and optical clarity are still readily apparent in the visible imagery as shown in Figures 7 and 8.

A number of specific issues with MODIS imagery have arisen that NASA science teams are currently working on. The stability and calibration of the sensors continues to be problematic. At present, issues with the Terra MODIS instrument are severe enough that NASA has placed a temporary hold on further processing of these data. MODIS Aqua data appear to be considerably more stable. On the MODIS instrument, multiple detectors result in a striping effect within the imagery. In addition, scan mirror side differences result in additional striping in scan line-groups

of 10. These issues, while evident within the imagery (Figures 7 and 8) are primarily an issue for extracting accurate quantitative biogeophysical measurements from the data and time series analysis for climate research. They are less of an issue for real-time operations relying on recognition of relative patterns within individual image scenes.

An operational X-Band tracking / reception dish is capable of receiving MODIS data in real time. Efficient code is available which allows processing of image products within the hour (depending on CPU availability). Information in the image data can be divided into that with accepted and published geophysical in-water accuracies and those for which relative patterns within an image are evident, their utility depending on the user.

MARLANT MetOc will be acquiring an X-Band receiver and satellite dish in 2006/2007 as part of the Polar Epsilon project. [personal communication, LCdr. Wayne Renaud, SSO, MARLANT MetOc]

6. Using civilian ocean observatories in Polar Epsilon

Monitoring and surveillance of coastal waters by maritime nations occurs both within the civilian and military communities. As identified throughout this report, there are commonalities between the two and as a result mutual benefit can be gained through cooperation.

This is already happening. Ocean observing infrastructure that is common to both communities is emerging throughout North America and is likely to expand significantly during the remainder of this decade.

North America's civilian ocean observing capabilities were reviewed recently [31]. Military monitoring and surveillance systems are largely classified, and therefore both the appended report and this DRDC report focus on civilian systems and unclassified military METOC products.

With the exception of infrastructure operated by the offshore oil and gas industry, operational civilian ocean observing infrastructure within North America is owned and operated by publicly funded agencies and institutions. Foremost among these are NOAA, NASA, Environment Canada, Fisheries and Oceans Canada and various U.S. based ocean observatories that are emerging within the U.S. university community. It is also noted that the U.S. Navy's Fleet Numerical Meteorology and Oceanography Center (FNMOC) in Monterey, California, provides a wide range of unclassified operational METOC products to the civilian community.

Canada's university community is also establishing ocean observatories. Their present status is such that they are likely to be of minimal operational benefit to Polar Epsilon within the short term, however, the University of Victoria, BC, has received funding to establish a substantive program (Neptune/Venus) in waters off the lower mainland of British Columbia. It focuses on seafloor and subsea properties but also includes a component pertaining to optical water properties. On the east coast, Dalhousie University has established a small observatory in Lunenburg Bay for research purposes and Memorial University has established a similar initiative in Bonne Bay.

Consideration of the appended report leads to the conclusion that marine waters bordering Canada and the USA have the greatest concentration of operational ocean observing infrastructure that is (a) relevant to Canadian waters and (b) required to develop the METOC capabilities of Polar Epsilon, as defined herein. This is due to the fact that in these areas data produced by American systems overlap into Canadian waters.

In addition to NOAA, FNMOC and NASA, three U.S. based civilian ocean observatories either provide or plan to provide operational METOC information for these border region waters [31]. They are the Gulf of Maine Ocean Observing System (GOMOOS – www.gomoos.org) on the east coast, the Northwest Association of Networked Ocean Observing Systems (NANOOS – www.nanoos.org) on the west coast, and the Alaska Ocean Observing System (AOOS – www.aoos.org) in the U.S. Arctic and northern Pacific waters.

Among these border region civilian ocean observatories, GOMOOS is the most advanced in terms of operational status and breadth of capabilities. It is also the only observatory that is experimenting with the use of RADARSAT data for operational METOC purposes, and it is the only one that includes membership from Canadian government, university and industry. It is also noted that GOMOOS' inaugural funding was provided by the U.S. Department of National

Defense. The primary research and development component of GOMOOS is located at the University of Maine.

From an operational perspective, the border region university-based ocean observatories are in a development stage. Presently, they are largely used as development and demonstration sites for monitoring hardware and software, marine models, data communications techniques, data management, processing and distribution infrastructure, and the ocean observatory concept itself. These objectives require a diverse range of spaceborne, shore-based and *in situ* platforms and sensors, some types of which have yet to reach the operational realms of NOAA, Environment Canada and Fisheries and Oceans Canada.

As shown previously in Table 1, the education and research community, which largely operates these border region observatories, is the only civilian community that requires all of the METOC parameters required by the defence, security and enforcement community. Combining this fact with their research, development and demonstration mandate results in these observatories fitting well with the objective of developing Polar Epsilon's METOC capabilities in support of advancing sensor performance, submarine operations, etc.

These observatories, for example, are North America's foremost source of operational synoptic maps of surface and near-surface current vectors, as provided by shore-based commercial HF radar systems and *in situ* acoustic Doppler current profilers (ADCPs). GOMOOS alone has three HF radar systems, one of which is located in Nova Scotia. Neither Environment Canada nor Fisheries and Oceans Canada provide actual surface currents on an operational basis, and Canadian Forces Raytheon HF radars are being installed for ship detection purposes, which places the radars too far apart for operational monitoring of surface current vectors [1]. GOMOOS programs located at the University of Maine also include an operational onsite L-band satellite reception facility for AVHRR and Seawifs data and an operational X-band satellite facility will be installed this spring to receive MODIS and OCM ocean colour data. Neither Environment Canada nor Fisheries and Oceans Canada have an X-band satellite reception facility for such purpose, and neither provide sea surface temperature (i.e. AVHRR) maps via the Web on an operational basis. In addition, U. Maine/GOMOOS has access to RADARSAT data collected by NOAA and provides NASA's Quickscat spaceborne scatterometer imagery for these border region waters.

6.1 Southwest Nova Scotia - a METOC / REA Demo Site

Successful development, testing, demonstration and utilization of any Polar Epsilon METOC product will require data collected by other sensors and platforms, and therefore will benefit from civilian ocean observing systems providing the appropriate suite of capabilities. GOMOOS, which focuses on the waters of the Gulf of Maine and Southwest Nova Scotia, ranks foremost among these systems.

This section of the report identifies operational imagery, data and information pertaining to waters off Southwest Nova Scotia that may be required to develop and demonstrate RADARSAT's METOC capabilities in support of the defence, security and enforcement sector. Where appropriate, proposed sources of operational data are identified and examples are presented.

6.1.1 RADARSAT satellite imagery

This report focuses on developing METOC capabilities in support of advancing sensor performance, rather than METOC *per se*. Therefore, it is appropriate and cost effective to use RADARSAT imagery from existing security, defence and enforcement programs. Once operational, this can be done with Polar Epsilon RADARSAT data. In the meantime, a Polar Epsilon METOC development program in the Gulf of Maine / SW Nova Scotia area could utilize RADARSAT data collected by Canada's ISTOP (Integrated Satellite Tracking of Polluters) program as well as RADARSAT data provided to GOMOOS / University of Maine via NOAA. The University of Maine already has hundreds of NOAA RADARSAT scenes of the area on file – in many cases along with their concurrent Quickscat, Seawifs, AVHRR, HF radar and *in situ* wind, wave, current and optical data. In short, this represents a very cost-effective opportunity for DRDC Ottawa and the Polar Epsilon project.

6.1.2 Ocean colour and SST satellite imagery

There are several sources of SST data for regional and global waters, however, the best operational sources in North America are all U.S. based. The University of Maine / GOMOOS has its own AVHRR L-band reception facility which it uses to generate operational SST maps of the area, daily and within minutes of satellite overpass. An example SST map derived in real time (i.e. within five minutes of satellite overpass) and available via the Web is shown in Figure 9 (www.seasurface.umaine.edu). NOAA and FNMOC also provide daily SST products via the Web. All provide both satellite and *in situ* SST data.

In Canada, Environment Canada and Fisheries and Oceans Canada do not post AVHRR SST maps to the Web on an operational basis. MARLANT MetOc has the same AVHRR L-band reception equipment as the University of Maine, however, this equipment is scheduled to be phased out in favour of MODIS SST imagery. Presently, MARLANT MetOc is producing a SST and ocean feature analysis twice weekly using NOAA's Satellite Active Archive. [personal communication, LCdr. Wayne Renaud, SSO, MARLANT MetOc]

During the initial stages, operational MODIS and OCM ocean colour products could be obtained via the operational X-band GOMOOS data reception facility located at the University of Maine (www.seasurface.umaine.edu). This system will be operational as of May 2005 and U. Maine is already developing MODIS products using data provided by NASA. Also in May, MARLANT MetOc will purchase MODIS software that allows processing of MODIS data provided by NASA / GSFC. Collectively, these sources will allow product development to proceed in the short term and will provide Polar Epsilon with a cost-effective means of evaluating the utility of data products based on these data.

The University of Maine also has the ability to receive Seawifs data directly via its L-band reception facility, as does MARLANT MetOc. Neither facility, however, is paying Orbital Sciences Corporation of Dulles, Virginia, the monthly fees that are now required to access these data. U. Maine generated operational Seawifs images prior to the change in data fees in December 2004, and an example Seawifs image is provided in Figure 10.

We note that the University of Maine will be purchasing operational OCM data from the Indian Oceansat satellite and therefore will have two sources of operational ocean colour data.

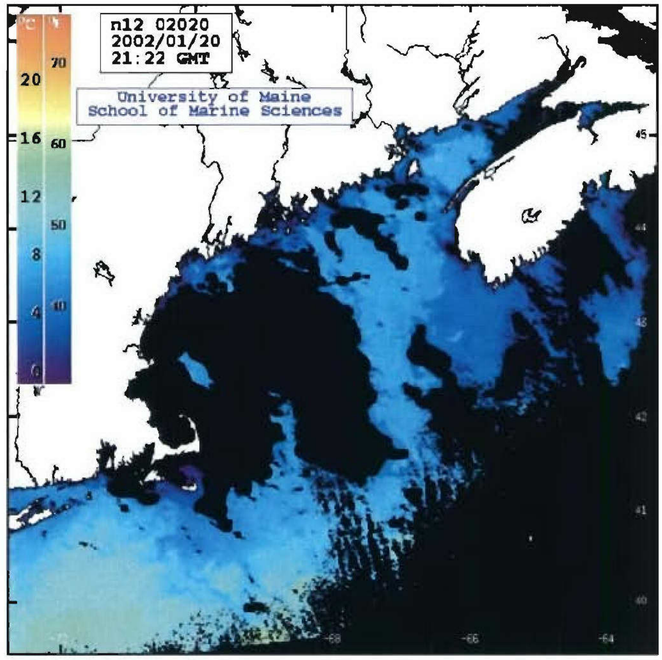


Figure 9. AVHRR sea-surface temperature map for the same date and location as the RADARSAT and Quickscat images shown in Figure 5. The time of overpass, however, differs by about 11 hours. Black areas indicate cloud cover

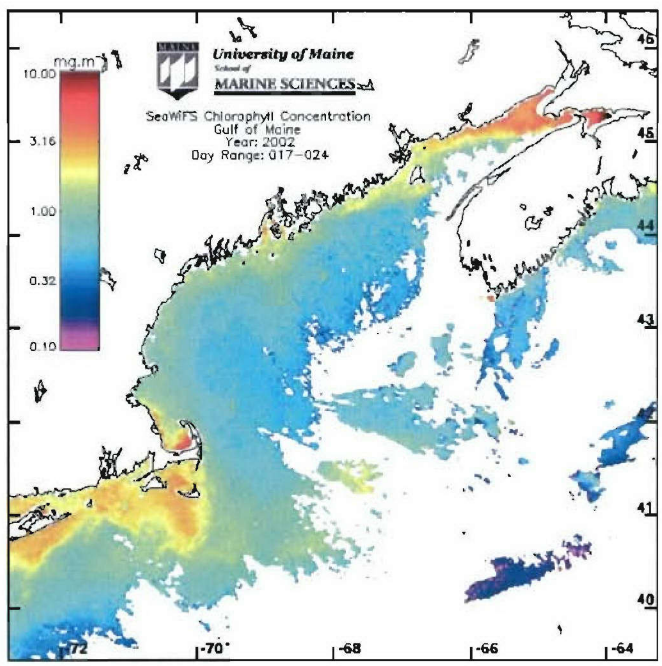


Figure 10. Seawifs seven-day composite image for 17-24 January 2002, which includes the time period of the RADARSAT, Quickscat and AVHRR images provided in Figures 5 and 9. White areas over water indicate persistent (i.e. over the seven-day period) cloud cover.

6.1.3 Ships of opportunity

In its early stages, a RADARSAT METOC development program could be supported using ships of opportunity. The Southwest Nova Scotia / Gulf of Maine region is a strong candidate for traffic of opportunity as it has established international traffic lanes involving vessels of a wide range of size and function, from small fishing craft to ferries and large tankers. There are oil refineries at Portland, Maine, and St. John, New Brunswick, and regular ferry runs between Yarmouth and Maine (Portland and Bar Harbor). In addition, Canada's east coast fleet of scallop draggers sail out of this area and are monitored routinely for their location by Fisheries and Oceans Canada.

6.1.4 Auxiliary METOC data

The civilian operational METOC community has advanced to the point where all of the auxiliary METOC data conceivably required to develop Polar Epsilon's METOC capabilities are available in near-real time, gratis, via the Web, as follows:

Modelled winds: In Canadian waters modelled winds are available from Environment Canada. The horizontal resolution of its two day forecast model (GEM – Global Environmental Multiscale) is 15 km over North America and adjacent oceans [www.weatheroffice.ec.gc.ca/model_forecast]. In support of Foreign Missions (i.e. for foreign waters) and also for North America, modelled wind vectors are available from FNMOC [www.fnmoc.navy.mil], including littoral winds from the U.S. Navy's COAMPS model (at 27 km resolution) and global winds from its NOGAPS model.

Spaceborne scatterometer winds: Both regional and global wind vectors from Quickscat / Seawinds are available via various Web sites, including GOMOOS, NOAA, NASA/JPL and FNMOC. MARLANT MetOc also uses these wind fields on a daily basis for operational purposes. These data are at 25 km resolution but NASA/JPL has demonstrated the processing of Quickscat data to 12.5 km resolution, for certain applications.

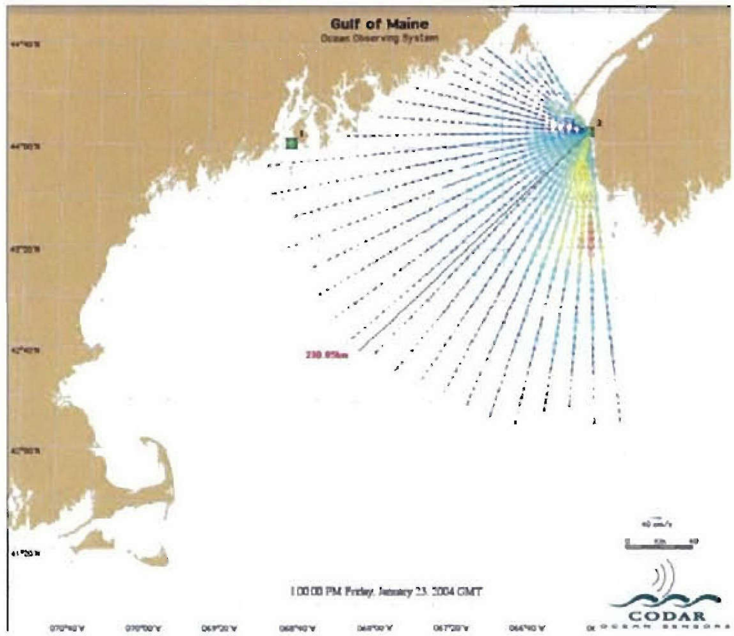
The GOMOOS wind product derived from Quickscat covers the precise geographic location of interest but blends wind data from successive passes of the sensor. An example of GOMOOS' blended wind product was presented previously in Figure 5(b). This blended product would not be the best Quickscat product for a RADARSAT METOC development and demonstration program. Instead, it would be preferable to use the Quickscat maps generated by MARLANT MetOc.

***In Situ* buoy data:** As a result of GOMOOS [www.gomoos.org], the Southwest Nova / Gulf of Maine region has an augmented network of *in situ* sensors whose data are available gratis via the Internet. This provides a unique source of *in situ* wind, wave, current and reflectance data. GOMOOS also has a variety of modeled products covering the entire region, including modelled surface winds, waves and currents.

Modelled waves: Regionally and globally modelled surface wave products are available via FNMOC - WW3 (wave watch 3). Fisheries and Oceans Canada also has an operational wave model in place, which includes the waters of Southwest Nova Scotia.

Synoptic surface current vectors: As a result of GOMOOS [www.gomoos.org], Southwest Nova Scotia and the Gulf of Maine have operational CODAR HF radar stations covering a portion of the region. Example current radials produced by GOMOOS' St. Mary's site are presented in Figure 11.

Figure 11. Inaugural surface current radials produced by the GOMOOS SeaSonde® HF Radar installation at St. Mary's, Nova Scotia. Note the inferred zone of current shear off SW Nova. Instrument specifications indicate offshore ranges should vary between 140 and 220 km, depending on local environmental conditions. Site 1 was not operating when this data was collected and therefore surface current vectors could not be derived.



As a component of this Technical Memorandum, current radials from this and another GOMOOS SeaSonde site (shown in Figure 11 as "1") were sampled over a one year period for their coverage at six am and six pm local time, which are the expected times for RADARSAT data. Results showed variations in offshore range that were within instrument specifications (140-220 km). Range is expected to vary with local environmental conditions.

7. Discussion and recommendations for DRDC Ottawa

7.1 RADARSAT REA Program for Project Polar Epsilon

Recommendation R1 – Wind Speed and METOC Features From RADARSAT

The primary recommendation of this report is to advance RADARSAT's ship and oil spill detection capabilities by initiating a RADARSAT REA program in support of Project Polar Epsilon. The purpose of this initiative is to operationally derive the following from RADARSAT imagery: (a) surface wind speed and (b) METOC features prevalent at low to moderate wind speeds and incidence angles. These *intermediary* products will be used to develop (i) an operational minimum detectable ship size product and (ii) an operational oil slick false target product.

The intermediary REA products have the potential to be used by MARLANT MetOc for forecasting purposes, and should be produced in a common, open source format, such as XML.

These products will improve the warfighter's and civilian user's confidence in RADARSAT and in using spaceborne assets for operational purposes. Canadian Forces operations could become centres of excellence in this field.

Recommendation R2 – Waves and Currents from RADARSAT not ready for REA

At this time, DRDC Ottawa should not proceed with implementation of operational wave or current products from RADARSAT.

Recommendation R3 – Use Seawinds Scatterometer Maps for REA

Recommendation R1 will require surface wind vectors derived from NASA's Seawinds scatterometer on Quickscat; specifically, those that are most concurrent with Polar Epsilon's RADARSAT imagery. These wind vectors are already provided gratis by NASA and NOAA and MARLANT MetOc already obtains and uses these data on a daily basis. DRDC Ottawa will need to establish a means by which to obtain these wind vectors from MARLANT MetOc, or alternatively, obtain them directly from NOAA.

In terms of overall demand within the marine community, the surface wind vector is the Holy Grail of surficial METOC parameters, but its value to the Polar Epsilon project does not pertain to weather forecasting or oceanography *per se*. It pertains to the fact that surface winds influence the performance of sensors, weapons, vessels and personnel used for purposes of defence, security and enforcement. Specifically, spaceborne SAR sensors used for ship, ice and oil detection and *in situ* acoustic sensors used for ASW and submarine operations. This view is consistent with the observation that the primary purpose behind NATO's REA programs is to

advance understanding of the state of the littoral battlespace in tactical time frames as a means to improve the performance of sensors, weapons, vessels and personnel.

Existing means to derive surface wind speed from RADARSAT data are sufficiently advanced to warrant development and implementation of an operational SAR wind product, in support of advanced sensor performance. The operational utility of this wind product arises because (a) RADARSAT's wind speed data are concurrent with RADARSAT data used to detect ships and oil spills and (b) other means available to collect these METOC data are either too removed in time or space from the location of the sensor to be of sufficient accuracy, or are too coarse in spatial resolution.

Polar Epsilon will overcome two barriers that have to date prevented implementation of an operational RADARSAT REA program: (1) it will provide the large number of required SAR scenes and therefore there is no need to justify the operational costs of SAR data solely on the basis of its value to METOC operations; and (2) it will provide the infrastructure required to deliver SAR-derived METOC products in operational time frames (i.e. for REA purposes).

A crucial requirement for obtaining wind speed information from RADARSAT is *a priori* knowledge of wind direction. The Seawinds scatterometer onboard NASA's Quickscat satellite is proving to be very useful in this regard as its orbit coincides favourably with that of RADARSAT. Civilian and military operational forecasting models are also being used for such purposes as are (i) certain meteorological features sometimes found in SAR images, and (ii) determination of the Doppler centroid anomaly in SAR imagery.

Polar Epsilon will operate RADARSAT at high incidence angles when searching for ships, which is not optimal for METOC feature detection or oil spill detection. Determining the priority of beam modes is beyond the scope of this report, other than to note that beam mode selection will influence ability to extract METOC parameters and features, and therefore Canada will need to rationalize and prioritize its deployment of RADARSAT in littoral waters.

Although the issue of rationalizing RADARSAT beam modes for the various government applications is beyond the scope of this report, information presented herein may contribute to the way forward in this matter as it defines the niche that spaceborne sensors occupy in a diverse network of ocean observing sensors, platforms and infrastructure. Only through consideration of the entire network can one hope to address all applications of national priority.

With respect to improving sensor performance, development of surface wave or current products from RADARSAT is of much lower priority than surface wind. Coincidentally, from a research perspective, techniques available to determine waves and currents from spaceborne SAR are not as robust as those available to determine surface wind speed from SAR. RADARSAT's ScanSAR mode has proven to be effective for ice, ship and oil detection but it is not optimal for wave detection, and wind induced waves (i.e., wind seas) are very difficult to measure in any routine way from polar orbiting SARs, which have a very large range-to-velocity ratio.

Surface current vectors cannot be derived from RADARSAT (1 or 2) data. Spaceborne SAR is capable of providing mean surface current gradients of radials, but the practical value of such data is not obvious. It is also capable of providing surface current radials if the surface currents are fairly strong, the winds are low to moderate, and the image is in sight of land. Radials are of practical value as they are useful for modelling surface currents, provided the models meet the operational requirements of the various high-priority applications, such as search and rescue and oil spill response. These applications require the actual current vectors (speed and direction) in a

wide range of wind conditions and geographic locations and in REA time frames. Research to date has concluded that a single satellite SAR mission does not have sufficient revisit time for such purposes.

It is noted that in recent years various organizations, including the Canadian Forces, have installed coastal HF radars, some of which are producing synoptic maps of surface current vectors in real time. There are approximately 200 coastal HF radars in operation world-wide, the USA is blanketing its shores with them, the U.S. Coast Guard has demonstrated their application to search and rescue, and their application to oil spill response was demonstrated last year in California [32]. In combination with coastal modeling, this alternative technology may become the norm for operational synoptic monitoring of surface currents in coastal waters.

7.2 METOC Features from Fused RADARSAT/MODIS Products

Recommendation R4 – Investigate Fused RADARSAT/MODIS Products

DRDC Ottawa and Polar Epsilon should investigate fused RADARSAT/MODIS products designed to diminish limitations inherent in both sensors. Target intermediary REA products include features such as fronts, eddies, internal waves and coastal pollutants of terrestrial origin, including oil and other plumes that influence surface roughness.

To date, there is insufficient development to recommend including fused RADARSAT / MODIS products in Canadian Forces REA operations, but there is sufficient development to warrant proceeding with further research and definition of required end products.

In order to fulfill this recommendation, DRDC Ottawa will require a research and development partner that specializes in ocean colour, preferably for military purposes. Establishing a working relationship with the U.S. Navy's ocean colour development group at NRL Stennis, or NATO NURC in Italy, would be logical choices.

The research community has not had the time series of concurrent SAR and ocean colour imagery required to develop fused SAR/ocean colour products for REA purposes. Polar Epsilon will overcome this limitation and thereby provide opportunity for advanced research and development in this field. In addition, the Canadian Forces' requirements for fused RADARSAT / MODIS products are not defined to a level which permits definition of specific fused products.

Having stated this, we speculate that a simple indicator of water clarity (e.g. turbidity) will be the priority product from ocean colour data for purposes of defence, security and enforcement in littoral waters. This parameter is derivable, for example, from 250 m resolution true colour MODIS products at a qualitative level, and from specialized 1,000 m resolution quantitative products such as synoptic maps of chlorophyll-a concentrations. An *in situ* sampling program is required to produce quantitative results as all of the applicable algorithms are derived empirically and algorithms derived for one body of water are not necessarily accurate in different bodies of water.

Under certain environmental conditions, the true colour MODIS product is capable of detecting ocean features that have been observed in SAR imagery, such as fronts, eddies, internal waves and shallow-water bathymetric features. Spaceborne SAR operating at low to moderate incidence angles (i.e. 20-47°) in combination with shored-based SeaSonde® (i.e. HF) radar has also been used to detect coastal plumes [32], which under certain conditions can be detected by spaceborne optical sensors. Specifically, the authors state that "*SAR appears well suited for characterizing runoff plume dynamics as a function of storm total precipitation, cumulative event discharge and timing of peak flow*" and "*...sea surface currents derived from HF radar can account for spatial distributions of oil slicks.*" Given that approximately 80% of the pollution entering coastal waters comes from terrestrial runoff [31], and that the Canadian government has already stated that addressing this issue is of high national priority [33], potentially, this observation has profound implications for the RADARSAT program and the Polar Epsilon project.

The fused SAR/ocean colour concept is not new but remains very much at a research level and has limited utility when the SAR sensor is operated at high or extreme incidence angles. This application would also prefer VV polarization over HH due to higher ocean backscatter for a given sea state and wind speed.

Unfortunately, the MODIS sensor on Terra is no longer functioning properly, NASA is no longer supporting the Seawifs calibration program, and the operational utility of India's OCM sensor on Oceansat is unknown at this point in time. With certainty, the OCM program is at a research level. Thus at this time, Polar Epsilon's use of spaceborne multispectral satellite sensors in support of defence, security and enforcement REA operations is limited to the MODIS sensor on NASA's Aqua satellite.

7.3 Using civilian ocean observing systems

Recommendation R5 – Use Southwest Nova Scotia for Product Development

The Polar Epsilon project, in cooperation with DRDC Ottawa and MARLANT MetOc, should utilize the waters off Southwest Nova Scotia for REA product development and demonstration. This will permit efficient and effective utilization of a wealth of existing Canadian and American civilian ocean observing infrastructure, particularly *in situ* sensors, environmental models and shore-based HF radars.

Globally, the civilian and military METOC communities are developing operational ocean observing systems, and they are doing so cooperatively. This report identifies broadly-based requirements for ocean observing infrastructure and substantial potential synergy between the civilian and military communities within the REA component of the Recognized Maritime Picture. This stage involves METOC data collection, processing, storage and dissemination. Beyond this REA component, the two communities diverge in terms of applications and ability to share common infrastructure. In addition to security aspects, a driving force behind this divergence is the civilian communities focus on using resulting data for meteorological and oceanographic purposes whereas the military's primary focus is advancing the performance of sensors, weapons, vessels and personnel.

Successful development and demonstration of REA products discussed herein will require data collected by various civilian sensors and platforms, and therefore will benefit from operational civilian ocean observing systems providing the appropriate suite of capabilities. Marine waters bordering Canada and the USA have the greatest concentration of operational ocean observing infrastructure that is (a) relevant to Canadian waters and (b) required to develop identified REA products. This is due to the fact that in these areas data produced by American systems overlap into Canadian waters. GOMOOS, which focuses on the waters of the Gulf of Maine and Southwest Nova Scotia, ranks foremost among these systems. These waters enjoy unprecedented operational monitoring from a METOC perspective and resulting operational data products are available gratis via the internet. Noted exceptions to this statement include operational data products that utilize Seawifs and OCM satellite data, both of which must be purchased.

Substantial components of these data have yet to find their way into the operations of Canadian Forces, Environment Canada or Fisheries and Oceans Canada. This represents an additional

operational opportunity for Polar Epsilon as in addition to ship and oil detection, these data are relevant to operations pertaining to search and rescue, habitat monitoring, pollution enforcement and environmental modelling.

The Polar Epsilon project is at the right place at the right time in terms of contributing to and benefiting from this trend towards cooperative civilian and military ocean observing. As a result, it is conceivable that Polar Epsilon will become the crystal upon which the government of Canada builds the spaceborne component of its operational ocean observing infrastructure.

8. Acronyms

ALI	Advanced Land Imager
AMSR	Advanced Microwave Scanning Radiometer
AOOS	Alaska Ocean Observing System
ASW	Anti-submarine Warfare
ATSR	Along Track Scanning Radiometer
AVHRR	Advanced Very High Resolution Radiometer
C4	Command, Control, Communications, Computers
COAMPS	Coupled Ocean Atmosphere Prediction System
COP	Common Operating Picture
DMSP	Defence Meteorological Satellite Program
DRDC	Defence Research and Development Canada
ERS	European Remote Sensing
ETM	Enhanced Thematic Mapper
FNMOC	Fleet Numerical Meteorology and Oceanography Center
GEM	Global Environmental Multiscale
GFO	Geosat Follow On
GIS	Geographic Information System
GOMOOS	Gulf of Maine Ocean Observing System
GSFC	Goddard Space Flight Center
HRG	High Resolution Geometric
ISR	Intelligence, Surveillance and Reconnaissance
ISTOP	Integrated Satellite Tracking of Polluters
MCM	Mine Counter Measures
METOC	Meteorology and Oceanography
MILOC	Military Oceanography
MODIS	Moderate Resolution Imaging Spectroradiometer
MMRS	Multispectral Medium Resolution Scanner
MSOC	Marine Security Operations Centre
NANOOS	Northwest Association of Networked Ocean Observing Systems
NASA	National Aeronautics and Space Administration (USA)
NATO	North Atlantic Treaty Organization
NOAA	National Oceanic and Atmospheric Administration
NOGAPS	Navy Operational Global Atmospheric Prediction System
OCM	Ocean Color Monitor
REA	Rapid Environmental Assessment
REP	Recognized Environmental Picture
RMP	Recognized Maritime Picture
SACLANT	Supreme Allied Commander Atlantic
SAR	Synthetic Aperture Radar
SSM/I	Special Sensor Microwave Imager
SST	Sea Surface Temperature
SubOps	Submarine Operations
T/P	Topex/Poseidon

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The Polar Epsilon project will use Canada's RADARSAT satellites to expand the Canadian Forces' space-based ship and oil spill detection capabilities in the Arctic, Atlantic and Pacific Oceans. RADARSAT's ability to detect ships and oil, however, is influenced by surface winds, waves and currents. As existing sources of meteorological and oceanographic data are too coarse in spatial resolution or too removed in time, this report investigates the feasibility of deriving such information from the RADARSAT imagery itself to conduct a rapid environmental assessment (REA) of (i) minimum detectable ship size and (ii) probability of oil spill false detection. The report also investigates methods to overcome limitations in Canadian Forces' deployed ocean observing infrastructure, which are required to develop and demonstrate spacebased REA products, by using civilian ocean observing systems. In addition, as a means of decreasing limitations inherent in space-based synthetic aperture radar and ocean colour sensors used by Polar Epsilon (i.e. RADARSAT and MODIS), the report identifies and discusses meteorological and oceanographic features of military interest that may be detected by both types of sensors.

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